WATER BOILER REACTOR PRINCIPLES AND EVALUATION

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by

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ABSTRACT

An exposition is presented of the elementary theory and basic engineering principles of the research type water boiler reactor. The various water boilers which have been built to date are discussed with a view toward illustrating these principles. Next, evaluations are made of the hazards and the educational utility of the water boiler, followed by a discussion of some of the administrative considerations encountered in its installation and operation.

It is concluded that the water boiler is a safe, dependable, and highly useful experimental device which is well suited to employment at an educational institution.

THE WATER BOILER REACTOR-PRINCIPLES AND EVALUATION

PREFACE

In December 1953 the writer received a list of thesis topics proposed by various members of the faculty of the United States Naval Postgraduate School. One such topic was "Feasibility of an Exponential Reactor", suggested by Doctor Austin Frey. Dr. Frey's intention (as understood by this writer) was that investigation be undertaken into the merits of installing an exponential reactor here at the U.S. Naval Postgraduate School for educational purposes.

An exponential reactor is one which contains a subcritical mass of fissionable material and thus requires an auxilliary neutron source to maintain its operation. The neutron flux produced by this source in the fissionable material is effectively multiplied by a factor $M = \frac{1}{1-k_{eff}}$ where k_{eff} is the reproduction factor of the fissionable material.

At first glance it seemed that for educational purposes the exponential reactor might offer certain advantages over the critical reactor especially with regard to safety and economy. It should be a sufficiently strong neutron source to serve ably as a training instrument but should not require as extensive shielding, cooling, control, and waste disposal systems as a critical type reactor. Favorable comment appears in the following quotation from the opening pages of AEC document ORNL860 dated 30 October 1950, entitled "Measurements

on the Orsort Uranium-Graphite Exponential Pile" by Campbell, et al:

> "As part of the facilities prepared for the course in experimental reactor physics of the Oak Ridge School of Reactor Technology, a uranium graphite exponential pile has been erected in the 101 bldg. at the Oak Ridge National Laboratory....."
>
> "As far as is known, this is the first exponential pile built principally for pedagogical purposes. As a teaching device for introducing engineers of the School into the intricacies of the uranium chain reaction it has many merits. Not the least important of these is that it is a safe device. Secondly, the thorough investigation of the neutron flux distribution in the exponential pile on the part of students can do much to give them a feeling for neutron physics which is the characteristic of a reactor engineer."

Although these remarks would seem encouraging, the following unfavorable comments were received in a letter to Dr.Frey from Dr. F. C. Vonderlage, Director of the Oak Ridge School of Reactor Technology:

> "Compared to a critical nuclear reactor, plans of which are available for educational purposes, exponential reactor use is very inflexible and the costs of the two are in the same ball park. We would not have built our exponential reactor

were it not for the fact that suitable surplus graphite was available for its construction, so that our costs were only for labor for its construction."

In view of Dr. Vonderlagé's remarks, the writer dropped further consideration of the exponential reactor and tentatively decided to look into the feasibility of employing a critical reactor at the U.S. Naval Postgraduate School. After consultation with Professor E. C. Crittenden, it was concluded that insufficient time remained to make a comparative study of all the available types of critical reactors; at his suggestion, the writer has restricted his thesis to the study of one type, viz, the water boiler. Another type, the "swimming pool", has been investigated by Major John B. Radcliffe, USAF. Thus the writer's report as it is now constituted, represents primarily a technical study of the water boiler type reactor with especial consideration given to the feasibility of employing it at an educational institution.

All information has been drawn from the unclassified literature of which there is a considerable quantity available. This restriction of source material seemed advisable, due to the limited available time, the difficulty in gaining access to the necessary classified documents, and the inconvenient and doubtful justifiability of putting the "restricted data" label on the student's thesis.

The writer's personal reason for the selection of this topic has been to acquaint himself with a field that will be of ever increasing military importance and which is closely related to his current military specialty.

The writer wishes to thank Doctors A. R. Frey, E. C. Crittenden, and J. R. Clark for their advise and assistance in the preparation of this paper.

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CHAPTER 1

INTRODUCTION

1.1 Evolution of the Reactor as an Educational Tool

Since the derivation of the Einstein mass-energy relationship ($E=mc^2$) early in the present century we have been confronted with the appealing concept of deriving large quantities of energy through conversion of relatively insignificant amounts of mass. Experimental confirmation of mass-energy conversion, however was not achieved until 1933 when Bainbridge successfully applied the Einstein equation to the analysis of artifically induced nuclear reactions. Although thereafter mass-energy conversion was repeatedly demonstrated in these phenomena, no means suggested itself for achieving this converstion on a macroscopic scale until the discovery of uranium fission in 1938*. It was then shown that under the proper circumstances a uranium nucleus could be split (fissioned) by a bombarding neutron into two roughly equal smaller nuclei plus two or three additional neutron. The energy liberated (converted) in such a process (approximately 200 mev) is unusually large for a nuclear reaction. The attractive possibility of somehow "persuading" the above product neutrons to produce further fissions and thus to institute a "chain reaction" received widespread attention and eventually resulted in the establish-

*Mass-energy conversion does occur in the chemical reaction; however the mass loss is so small that it is undectable experimentally.

ment in this country of the Manhattan Project and later its successor, the Atomic Energy Commission. The success of these organizations culminating in (among other accomplishments) the development of the atomic bomb and the nuclear reactor is well known.

Nuclear research, of course, has been greatly stimulated on all levels by these events. The many engineering problems posed by chain-reacting systems have given rise to a new brand of specialist, the nuclear engineer. Accordingly, a number of universities about the country have installed nuclear engineering curricula. A leader among these is North Carolina State College. To implement its course of instruction, this institution has constructed an actual nuclear reactor on the campus. It is felt that this reactor will be a valuable research and pedagogical aid not only in the nuclear engineering field, but also in a number of other fields as well, such as pure physics, radiation chemistry and bioradiology. It seems likely that other universities will take similar steps in the near future.

1.2 Objective of this Paper

The question now naturally arises: In view of the very special interest of the Armed Forces in the fields of nuclear physics and engineering, would it be desirable and feasible for the United States Naval Postgraduate School to undertake the construction of a reactor for educational and research purposes? The writer does not feel adequately qualified or in a position to completely discuss the question; however,

a number of general comments regarding it will be offered. Essentially he has confined himself to a technical study and evaluation of one type reactor which he believes would be suitable should the need for a reactor at the school be deemed to exist.

1.3 Review of Elementary Theory

1.3.1 Conservation of Mass-Energy

The sum of the total energy plus the energy equivalent of the total mass of any system undergoing a nuclear or chemical reaction remains constant. This may be expressed by the formula:

$$E = mc^2$$

where:

E is the increase of energy appearing in the system

m is the loss of rest mass in the system

c is the velocity of light.

It is evident that because of the large value of c any small decrement of mass will result in a large release of energy.

1.3.2 Structure of Nucleus

The nucleus of an atom consists of an integral number of nucleons (protons and neutrons). For the light stable nuclei the number of neutrons approximately equals the number of protons. As the nuclear mass increases, the neutron to proton ratio of the stable nuclei gradually increases, reaching a maximum of about 1.5 near the end of the periodic table.

1.3.3 Binding Energy

The binding energy is the energy required to completely resolve a nucleus into its constituent protons and neutrons. Two types of force fields exist in the nucleus: (1) that due to proton-to-proton electrical repulsion; (2) that due to nucleon-to-nucleon short range attractive forces. The difference between the attractive and repulsive energies due to these forces is equal to the binding energy. If the binding energy per nucleon is plotted against mass number for all available nuclei the points are found to fall roughly on a smooth curve which rises sharply from 2.2 mev to a maximum of about 8.7 mev at a mass number of about 60, then tapers off to about 7.6 mev at the high end of the periodic table.

1.3.4 Nuclear Reactions and Cross Section

A nuclear reaction may be defined as an interaction of a target nucleus with a projectile neutron, proton, photon, electron, or another nucleus. In nearly all cases pertinent to reactor theory, the projectile is a neutron. The reaction occurs in two stages: (1) The projectile is absorbed into the nucleus thus losing its identity and forming a compound nucleus. (2) After an extremely short time (usually) the compound nucleus disintegrates into two or more fragments. A useful term in connection with nuclear reactions is the nuclear cross section (σ) which may be defined as the apparent cross sectional area of the nucleus within which a projectile particle must strike to produce a given

reaction. The so-called macroscopic cross section is the product of the nuclear cross section and the number of target nuclei per unit volume. The values of these cross sections vary widely with the energy of the projectile particle.

1.3.5 Neutron and Neutron Flux

The effects of neutrons upon matter vary considerably with their energy. It has thus been found expedient to designate the neutrons as fast (10 mev-10 kev), intermediate or resonant (10 kev - .01 ev) and slow or thermal (below .01 ev). The rate at which a group of neutrons diffusing through a block of matter produces effects is evidently related to the total track length travelled by these neutrons every second; thus it has been convenient to define a term neutron flux which represents the total track length per second travelled by the neutrons in a cubic centimeter. The mathematical representation is:

$$\phi = \sum n_o v_o$$

where

ϕ = neutron flux in neutrons per cm^2 per second

n_o = density of neutrons of speed v_o in neutrons per cc.

A summation is then taken over the velocity range under consideration. Such terms as fast flux, resonance flux, and thermal flux are in common use and their meaning is self-evident.

1.3.6 Fission

Neutron capture by certain heavy nuclei will, under proper conditions, result in their rupture into two

roughly equal fragments. These fragments will have approximately 0.9 mev less binding energy per nucleon than parent nuclei and an unstable excessive neutron-to-proton rate. The fragments approach stability by beta or neutron emission. In the fission of U^{235} by slow neutrons, it is found that an average of 2.5 ± 0.1 neutrons are emitted per fission. About 99% of these are termed prompt neutrons and are emitted within 10^{-14} seconds. The remaining 1% are delayed neutrons and are emitted at varying intervals up to about 55 seconds. These evolve from certain of the fission products which undergo one beta decay and then emit a neutron.

Three fissionable isotopes are important in reactor technology, viz, U^{235}, Pu^{239}, U^{233},. These materials will fission with both fast and slow neutrons; their cross sections, however, are much greater for slow neutrons. U^{235} occurs in natural uranium, U^{233} is made by neutron bombardment of Th^{232} and Pu^{239} is made by neutron bombardment of U^{238}.

1.3.7 Scattering of Neutrons

Scattering is any nuclear process in which the overall result is only the transfer of energy from one particle to another; i.e., the expelled particle is identical with the incident particle. Neutrons may undergo inelastic (momentum, but not kinetic energy conserved) or elastic(both momentum and energy conserved) scattering with target nuclei. The former type occurs principally with fast neutrons and heavier nuclei; the target nuclei are left in an excited state and radiate gamma photons. Elastic scattering may be

treated analytically as a billiard ball collision. The greatest average energy transfer occurs when the projectile and target masses are equal. Thus in the case of the neutron, the transfer is maximum for hydrogen nuclei and falls off with increasing nuclear mass. At certain projectile energies, the compound nucleus that is temporarily formed in the scattering process will exist at or near one of its quantum states. The elastic scattering cross section for such projectile energies is unusually large, and the process is termed resonance scattering.

1.3.8 Chain Reaction and Criticality

Consider any sort of assembly of enriched uranium and auxilliary non-fissionable materials. Fast neutrons introduced into the uranium mass may suffer one of several fates: (1) May escape from the assembly; (2) May be captured by U^{238} or (less likely) by U^{235}; (3) May be captured by the auxilliary materials or impurities; (4) May fission U^{235} or U^{238}; (5) May be thermalized by scattering and then fission U^{235}. If the number of neutrons produced in processes (4) and (5) just compensates for those last in all five processes, there will exist a self-sustaining chain reaction and the assembly is termed critical. If the number of neutrons produces exceeds the number lost, the neutron density and rate of energy release will increase with time and the assembly is termed super-critical. If the number of neutrons lost exceeds the number produced, the reaction dies out and the assembly is termed subcritical.

It is evident that the relative probabilities of the above five processes and thus the criticality will depend, among other things, on the mass and geometry of the uranium. The terms "critical mass" and "critical size" are employed to indicate the quantity of uranium present just at the point of criticality.

1.3.9 Reactor Theory

Several mathematical studies have been made of the behavior of neutrons in scattering, absorbing, and multiplying media. With the aid of equations from these studies, estimates can be made of the critical size of proposed assemblies containing fissionable material. Since it was necessary, however, to resort to simplifying assumptions to derive these equations, estimates based upon them may be in error on the order of 10 to 20%; thus such estimates must always be confirmed experimentally. No effort will be made to summarize "reactor theory" here. Several excellent references appear in the bibliography.

1.4 Reactor Concept

A reactor is a system of fissionable material and proper auxilliary material and equipment which has been suitable arranged and engineered to produce and sustain a safe, controllable, useful chain reaction.

1.4.1 Classification of Reactors According to Neutron Energy

Reactor design varies considerably depending upon whether it is desired to cause fission with fast, intermediate,

or thermal (slow) neutrons. Only thermal reactors have been declassified and are of much pertinence to this report. Fast reactors present greater problems of safety and control, require a greater quantity of fissionable material to achieve criticality, and will not operate on fuels which contain more than a low concentration of U^{238}. The remainder of this report will deal almost exclusively with thermal reactors.

1.4.2 Classification of Reactors According to Function

(1) Power Plant-Reactor is used as a heat source in a thermodyhamic engine.

(2) Production Plant-Advantage is taken of the neutron flux to manufacture Pu^{239} from U^{238} or U^{233}, from Th^{232},; other radioisotopes can also be obtained either by neutron irradiation or fission product extraction.

(3) Research and/or Educational Facility-Neutron flux is utilized for research and training in nuclear physics, nuclear engineering, and a number of other fields.

1.5 Components of a Thermal Reactor

1.5.1 Fuel (Fissionable Material)

The most common fuel at present is enriched or natural uranium; however, Pu^{239} or U^{233} can also be used. The fuel may be present in the liquid or solid state as an element or compound. It is essential, however, that the other con-fissionable elements present have a low neutron capture cross section.

1.5.2 Moderator

Fission neutrons are essentially fast neutrons with energies averaging 1 or 2 mev and ranging up to about 15 mev. The fission cross sections for U^{238} and U^{235} at these energies are quite low. Neutron capture (without fission) by both U^{238} and U^{235} is a serious competing process; in fact, a homogenous mass of pure natural uranium will not sustain a chain reaction because too many neutrons are lost to capture. At thermal neutron levels the fission cross section for U^{235} is very high. The thermal reactor has been designed to take advantage of this fact by slowing (moderating) most of the neutrons to thermal energies before allowing them to cause fissions. Consideration must be given to the fact that U^{238} exhibits a high resonance capture cross-section at 5 ev so that a considerable number of the decelerating neutrons will be lost at this level. The design must circumvent this problem by slowing the neutrons as rapidly as possible, decreasing the relative concentration of U^{238} (i.e. increasing enrichment in U^{235}) and/or arranging the geometry of the reactor assembly so that a substantial number of the neutrons are not in the vicinity of U^{238} atoms as they decelerate through the 5 ev resonance level.

Moderation is accomplished by means of an auxilliary material which is used to scatter the fission neutrons and thus deplete their energy. This material frequently is intimately mixed with the fuel material, and the reactor is designated as a homogenous type. On other

occasions (especially in natural uranium reactors), lumps or rods of fissionable material are dispersed in some pattern throughout the moderating material; the reactor is then designated as a heterogenerous type.

The ideal moderator should have a low capture cross section, a high scattering cross-section, and a large average energy transfer per scatter. The last requirement dictates use of the light elements. Deuterium (in the form of heavy water), beryllium and graphite are the best practical moderators. Hydrogen (in the form of water) is often used. It is ideal with respect to the last two requirements, but somewhat poor with regard to the first. It cannot be used in a natural uranium reactor.

An index of moderator performance is given by the moderating ratio:

$$R = \xi \frac{\sigma_s}{\sigma_c}$$

where

$\frac{\sigma_s}{\sigma_c}$ is the ratio of scattering to capture cross sections and ξ is the average value of the natural log of the ratio of the neutron energy before a collision to that after the collision.

1.5.3 Reflector

To reduce the neutron flux leaking from the fuel-moderator core, it is expedient to surround the core with a reflecting material which will scatter back some of the neutrons. The requirements for this material are similar to those

of the moderator. Graphite and sometimes beryllium are usually used. By reducing neutron leakage losses, the reflector can materially reduce the mass of fuel required for criticality.

1.5.4 Shielding

Protective shielding is necessary from the hazardous neutron and gamma rays emitted from the reactor. These two radiations require different types of shielding. In most cases it is desirable to shield out the neutrons first since otherwise these will undergo capture or inelastic scattering reactions in the gamma shield which give rise to additional gamma rays.

Neutrons can only be effectively eliminated by capture reactions. In general, capture cross-sections are appreciable only for thermal neutrons. A good shielding procedure is first to moderate the fast and intermediate neutrons with appropriate substances, and then to absorb all the thermalized neutrons with a suitable absorber. The fast neutrons may be moderated by inelastic scattering with elements of high atomic number placed close to the core, so that the resulting gammas can be more easily shielded. The intermediate neutrons can be moderated by elastic scattering with light elements, the best of which is hydrogen. Finally, the thermalized neutrons can be eliminated with an absorbing material of high capture cross-section which does not radiate appreciable gamma. Boron and lithium are good.

Gamma rays are effectively shielded by dense

materials. Heavy concrete and lead are commonly used. Large quantities of water are sometimes used.

Shielding problems also exist in connection with the coolant, disposal of wastes or handling of any material or item which has been irradiated.

1.5.5 Cooling

The great bulk of the energy liberated in fission will appear as heat in the core. This is generally removed by circulating a liquid through the core. Desirable characteristics for this liquid are a high moderating ratio, low susceptibility to induced radioactivity, high density, high specific heat, high heat transfer coefficient, and low vapor pressure. In some applications this fluid acts a heat source for an external engine. Water is a common coolant. For power applications, certain liquid metal coolants are being investigated.

1.5.6 Control System

The number of fissions produced in one generation of neutrons by one fission in the preceding generation is known as the reproduction factor (k_{eff}). It is evident that this factor must be rigidly controlled. In steady state operation it is kept equal to one. During an increase of power level, it is kept between 1 and 1.01. In reduction of the power level it must be less than 1. The above figure of 1.01 is derived from the fact that 1% of fission neutrons are delayed (see sec. 1.3.6) When k is between 1 and 1.01 perpetuation of the chain reaction is absolutely dependent upon these delay

neutrons. Because of the fact that they are delayed, increase in power level (when 1 k_{eff} 1.01) proceeds reasonably slowly and is thus far more amenable to control than would otherwise be the case. If k_{eff} exceeds 1.01, the assembly is said to be prompt critical.

The reproduction factor may be varied by altering the geometry of the fuel, moderator, or reflector. A more convenient method, however, is to introduce variable amounts of neutron absorbers into the reactor. Cadmium and baron are often used. Normally the absorbers are placed on the end of "control rods" and inserted through tubes to varying distances within the fuel, moderator, or reflector. The control system must provide for fine, coarse, and safety control. Because of continual small ambient fluctuations in k it is desirable that fine control be automatic. The safety control should be capable of rapidly shutting down the reactor in the event of faulty operation.

To facilitate control suitable instrumentation must be provided for indicating radiation and temperature levels at appropriate points.

1.5.7 Exposure Facilities

For research and educational purposes, easy access to the neutron flux must be obtainable. Holes, ports, channels, etc. must be provided into and through the reactor and constructed in such a manner as to minimize the radiation hazard to personnel. In order to obtain a pure thermal flux a thermal column is generally provided. This is simply a long column of moderating material (almost always graphite) one end of which terminates at the core of the reactor.

CHAPTER 2

PRINCIPLES OF WATER BOILER REACTOR

The homogenous water boiler seems to offer a number of advantages as a research and educational tool. Los Alamos and at least two other agencies have explored its possibilities. Accounts of their programs will be rendered later.

The core of the water boiler is simply a tank filled with an aqueous solution of some compound containing fissionable material. The reactor consists of this core plus the necessary systems for shielding, cooling, loading, etc. Due to the heating of the fuel solution during operation, the reactor has been christened "water boiler"; however, in normal operation, the temperature is kept below the boiling point. The basic components are discussed below.

2.1 Fuel

Normally, the fuel compound is a salt enriched in U^{235}. A number of factors must be considered in the selection of this compound.

(1) It must be adequately soluble for the critical concentrations needed.

(2) It should contain no element (other than the fuel element) having a high neutron capture cross-section.

(3) It should not be corrosive to the container or inserted piping.

(4) It should be chemically stable and not undergo appreciable radiolytic decomposition, nor form precipitates and volatile or corrosive substances.

(5) The uranium should be easy to separate without appreciable loss should purification be necessary because of fission product or other contamination.

(6) It is desirable that the boiling point of the solution be as high as possible.

Both uranyl sulfate and uranyl nitrate have been successfully used. The nitrate is superior in items (3), and (5); the sulphate is superior in items (1), (2), (4) and (6).

2.2 Moderator

The water of the solution acts as its moderator. Since hydrogen thermalizes fast neutrons in relatively few collisions, its employment permits the use of a rather small volume of solution for criticality; however, because of the rather high capture cross-section of hydrogen substantial enrichment (in U^{235}) is required. Otherwise the hydrogen and U^{238} losses together would be sufficient to prevent the establishment of a critical state. The use of enriched fuel is desirable for other reasons which will be brought out later.

2.3 Fuel Tank

2.3.1 Shape

The shape of the fuel tank is important in determining the critical mass. To achieve criticality with a minimum mass of fuel, a spherical shape should be used. A sphere has the least surface for a given volume. Neutron

leakage which depends upon surface is thus minimized. Normally the tank will be pierced with numerous tubes for cooling, experimental exposures, control rods, gas disposal, instrumentation, etc.. Engineering considerations relative to the optimum practical arrangement of these facilities and their effect upon critical size and shape may perhaps indicate that a fuel tank shape somewhat other than spherical is more advisable.

2.3.2 Structural Material

The following criteria govern selection of a structural material.

(1) Neutron absorption in the tank material must be minimized. Thus it is desirable that the material have a low capture cross-section and be as thin as practicable. The efficiency of the reflecting material which normally is place around the tank is limited by the neutron "transpacency" of the tank material

(2) The material must be resistant to normal or radiolytic induced chemical reaction with the tank contents.

(3) The material must have adequate tensile strength, must be leak-proof, and should be heat resistant. Type 347 stainless steel is found to be very suitable.

2.4 Cooling System

Cooling is provided by one or more stainless steel coils passing through the tank. The coolant is usually tap water which in most cases may be disposed of in the normal sewage system after a reasonable holding period in underground tanks

2.5 Reflector

The fuel tank is normally encased in a graphite or beryllium oxide reflector. Beryllium is the superior reflector but has the disadvantage that it undergoes a gamma neutron reaction. This creates the effect of having a variable neutron source in the reactor during the startup and shutdown.

2.6 Control System

Cadmium or boron tipped rods are used as described in Sec. 1.5.6. These extend into the reflector adjacent to the tank or enter thimbles in the tank itself. The latter method has the advantage of minimizing "shadow" effects on experimental exposure facilities.

2.7 Shielding

Shielding of the water boiler follows the general principles outlined in Sec. 1.5.4. The major portion of the shielding is generally a mass of concrete, surrounding most of the reflector. The concrete mass is also useful as an aid in protection against sabotage.

2.8 Gas Disposal

One disadvantage of the water boiler lies in the fact that the fission fragments from the fuel are released directly into the water moderator. These ions have sufficient energy to sever the chemical bonds of many water molecules, and as a consequence, there is a considerable hydrogen-oxygen efflux during reactor operation. These gases carry with them traces of fission products plus vapor and droplets from the fuel solution. The overall mixture thus represents both an explosive and a radioactive hazard. The explosive hazard can be effectively eliminated with a recombination system, an example of which will be described in Sec. 3.3.7

The hydrogen and oxygen are recombined into water and returned to the solution. In the process many, but not all of the radioactive elements are returned as well. The recombination system thus reduces the radioactive problem of gas disposal, but does not eliminate it. Several possible safe methods of gas disposal are the following:

(1) The gas could be passed through a long (on the order of 1100 ft.) underground delay pipe line, diluted about 100,000 times with air, and then discharged from a 150 ft. stack.

(2) The gases could be held for a long period in large underground tanks, then flushed out the stack with air.

(3) The gases could be forced through an activated charcoal absorption trap. Such a trap will remove nearly all activity. It has been calculated at Los Alamos that 100 kg of charcoal would be adequate to decontaminate the gas stream from the SUPO water boiler (Sec. 3.3) for a one month period. This 100 kg could be allowed to stand for another month, during which time sufficient decay would occur to allow the active isotopes to be concentrated in a small tube and buried.

2.9 Loading and Criticality

Loading and unloading of the tank is best accomplished by applying pressure or vacuum to the tank as needed and allowing the fluid to enter or leave the tank through a small attached tube. Care must be taken in the initial

approach to criticality to prevent accidental overloading. The tank should first be largely filled with distilled water. Addition of fuel is then made by pumping out a portion of the tank fluid, and adding fuel in highly concentrated form, and then pumping the mixture back into the tank. After each addition, a large portion of the liquid should be flushed in and out of the tank about 10 times to ensure adequate mixing.

In the approach to criticality, the reactor is operated exponentially, using an external neutron source (such as a Ra-Be type) placed within a tube within the reactor. As mentioned in the preface, a sub-critical assembly has the faculty of effectively multiplying the flux from such an external source according to the formula: $M = \frac{1}{1-keff}$ where M is the multiplication and keff is the effective reproduction factor. As small additions are made to the fuel mixture, count rate measurements are recorded at selected points close to the tank. A plot is made of the U^{235} added versus the relative reciprocal counting rate (i.e., 1/M). An example of such a plot is shown in Fig 1. As criticality is approached, the plot becomes approximately linear so that an estimate of the critical mass may be obtained by extrapolating the curve to the horizontal axis. As the quantity or uranium approaches this value, additions of fuel should be made in very small steps. In the immediate vicinity of the critical point, the criticality status may be ascertained by suddenly removing the external neutron source and observing

the effect on the count rate. If the count rate drops, the assembly is sub-critical. If the count rate was previously rising and levels off upon removal of the source, the assembly is critical. If the count rate has been rising and continues to rise, the assembly is super critical.

Upon reaching a stage of slight super criticality, control is established with the control and safety rods. A small additional quantity of fuel is added to permit adequate flexibility of rod control to allow for fuel "burnup", and to compensate for neutron absorption by experimental apparatus and by accumulating fission products.

2.10 Temperature Coefficient

It is found that the critical mass increases with temperature. There are two reasons for this. First, an increase in temperature expands the "soup", resulting in an increased mean free path for the neutrons and thus an increase in the neutron leakage. Second, an increase in temperature results in an increase in the average thermal neutron energy; this effect results in a further increase in mean free path, since the fission cross-section of U^{235} drops off with increasing neutron energy.

It is found convenient to define a temperature coefficient $\frac{dk_{eff}}{dT}$ where k eff is the effecting reproduction factor and T is the temperature for all water boilers in current use. This coefficient is negative and has a magnitude on the order of 1 or 2 x 10^{-4} per degree Centigrade. The magnitude increases somewhat with temperature.

The negative temperature coefficient is an aid in maintaining a constant power level in the reactor. Any perturbation in the power level will produce a transient change in k which tends to restore the original power level. The control rods will have a different equilibrium position for every power level. These positions will vary somewhat with fluctuations in cooling coil efficiently.

2.11 Limitations on Power Level

The maximum power level obtainable in a water boiler is determined essentially by three factors.

(1) Temperature - The cooling system must be adequate to keep the fuel mixture well below the boiling point. Excessive temperatures decrease the reactivity and produce undesirable high pressures in the tank.

(2) Radiolytic Decomposition of Water - Excessive power levels intensify the problem of gas disposal and recombination. In addition, the formation of bubbles decreases the reactivity.

(3) Radiation Levels - The amount of shielding required increases with the radiation level which is a function of the power level. The maximum power level designed to date into a research water boiler reactor is about 45 KW (SUPO).

CHAPTER 3

DISCUSSION OF RECENT WATER BOILER PROGRAMS

Several groups of the United States have constructed and operated research water boilers. Interesting features of each device are described below;

3.1 Los Alamos Program - LOPO

In 1943 at Los Alamos it was decided to construct a water boiler operating at about 1 KW in order to gain experience in the operation of a critical assembly using a minimum of active material. Initially a low power pilot model, LOPO, was constructed. See Fig 2.. A uranyl sulfate solution was used as the fuel mixture. The uranium was enriched to 14.6% U^{235}. Calculations showed that for this order of enrichment a spherical tank of 1 ft. diameter would minimize the fuel required for criticality. Below the tank is a conical dump basin of non-critical geometry. LOPO was brought to criticality in May, 1944, using the exponential method described in Sec. 2.9.. Additions of the active salt were made to portions of the solution in the dump basin which were forced into the tank pneumatically. LOPO was never operated at over 50 milliwatts and thus required no cooling system.

3.2 Los Alamos Program - HYPO

3.2.1 - General

After success with the pilot model LOPO a higher power boiler HYPO was constructed to be used as a strong

neutron source for research (See Fig. 3 thru 6). At the maximum power level of 6 KW, the neutron flux at the center was $3 \times 10^{11} n/cm^2$ -sec..

A number of improvements were incorporated in HYPO to include the addition of research facilities and a number of safety features. Uranyl nitrate instead of uranyl sulfate was used as the fuel to permit ether extraction of the fission fragments.

The major components of HYPO are shown in Fig. 3:

(1) 12 in. diameter, 1/16 in. thick stainless steel fuel tank.

(2) Inner Be O reflector

(3) Supplementary Graphite Reflector. Graphite blocks may be removed to provide exposure facilities. Two drip pans installed in the reflector prevent solution loss in case of a leak.

(4) Cooling coil, pipes for flushing air and level Indicators are not shown.

(5) "Glory hole", tube through tank for obtaining maximum neutron flux.

(6) Thermal column

(7) Bismuth shield to remove gamma rays from thermal column.

(8) Cadmium "shutter" for thermal neutrons in the thermal column.

(9) 1/32 in. Cd shield for slow neutron capture, plus 4 in. Pb shield for resulting gammas.

(10) 5 ft. concrete gamma shield.

3.2.2 Cooling System

A six turn cooling coil with a ½ in. inner diameter and an effective length of 157 in. is inserted into the sphere (see fig. 5 and 6). The cooling tube was overdesigned to take care of the possibility that bubbles from the radiolytic decomposition of the water might cut the cooling efficienty 50%. After assembly it was found that the designed flow (50cc/min. entering the coil at 5°C) would permit 6 KW operation the year round. The outlet water was routed through a compartmented tank within the shield, and then out underground to a creek 200 ft. away. The delay permitted the short-lived radioactivity to die out.

3.2.3 Loading and Criticality

The critical mass for HYPO turned out to be 808 gm U^{235} as compared to LOPO's 565 gm. This addition was due to the change in fuel compound, lowering of the fuel enrichment, addition of cooling coil and glory hole, and increase in sphere thickness. Further fuel was also added to allow for control rod regulation, absorption experiments and temperature fluctuation (temperature coefficient = 1.33 gm $U^{235}/^{\circ}C$). The level of the fuel was maintained between 3 and 4 cm from the top of the sphere with the aid of two level indicators. Loading was performed pneumatically through a tube inserted through one of the indicators.

3.2.4 Gas Disposal

To prevent explosion of the gaseous efflux (see Sec. 2.8), the gases were diluted and flushed by pumping in 50 cc air per minute. The gas mixture was routed through a

solution safety catching device, then underground through silica gel drying tanks and finally released 2000 ft. from the building. About 30% of the fission product activity was carried away by the gases. It is doubted that this disposal system would be satisfactory in a heavily populated area.

3.2.5 Exposure Facilities

A number of transverse and longitudinal ports containing removable graphite bricks extended through the thermal column. The transverse ports pierced completely through the column and the longitudinal ports extended to the cadmium shutter (Fig. 3). Two additional ports were drilled to line up with the sphere "glory hole". There were also a number of vertical ports for monitoring equipment. Ports extending through the concrete were normally plugged with wood capped with cadmium and two inches of lead. The two ports opposite the glory hole were shielded by 4 inch thick lead doors.

3.2.6 Control

Four cadmium rods provided control: a safety rod, a shim (coarse control) rod, and two (fine) control rods. These rods were located in channels in the reflector adjacent to the sphere. In the event of excessive neutron flux, or failure of the flushing air or water systems, the safety and control rods were dropped into place by electromagnetic release mechanisms.

3.2.7 Formation of Precipitate

After 1000 kilowatt hours, a precipitate was formed. This was due to a gradual loss of nitrogen into the gaseous efflux and was remedied by regular addition of small quantities of nitric acid and water.

3.3 Los Alamos Program - Supo

3.3.1 General

In 1950 and 1951 alterations were performed on HYPO to make it a more useful and safer experimental tool. The neutron flux was increased, the experimental facilities were improved and the explosion hazard in the exhaust was removed. The entire sphere core assembly was replaced. The modified structure was christened SUPO (see Fig. 7 through 13). The new power level is 45 KW and the maximum available neutron flexes are: thermal 1.7×10^{12} n/cm^2-sec, intermediate 2.8×10^{12} n/cm^2-sec; fast 1.9×10^{12} n/cm^2-sec.

3.3.2 Cooling System

To permit the above levels the former single cooling coil was replaced by three 20 ft. ¼in.O.D., 3/6 in. I.D. stainless steel tube (see Fig. 10).

3.3.3 Reflector

The former combination Be O - graphite reflector was replaced by an all graphite reflector. This allows more rapid and complete shutdown, and eliminates a variable starting source which resulted from γ-n reactions on the beryllium.

3.3.4 Fuel Enrichment

Since carbon is a poorer reflector than beryllium, it was necessary to increase the fuel enrichment to 88.7%; this allowed continued use of low uranium concentration. The critical mass is 777gm U^{235} and the operating mass is 870gm (as in HYPO). Due to the increase in enrichment in SUPO, there is a decrease in the total amount of uranyl nitrate present and thus the necessity for additions of nitric acid (Sec. 3.2.2) is less frequent.

3.3.5 Control

Two additional control rods were added; these move directly into the sphere via reentrant thimbles. The absorber used is B^{10}. Additional control was required by the switch to an all graphite reflector.

3.3.6 Alterations in Exposure Facilities and Shielding.

The exposure facilities were increased. A new high-flux port to supplement the glory hole is tangent to the sphere and runs completely through the reactor. The original thermal column on the south side was completely rebuilt with improved shielding and more ports. Some of the shielding on the north side was removed and an additional thermal column built. All Cd shielding was replaced by B_4 plus paraffin.

3.3.7 Recombination System

The gaseous efflux problem (see Sec. 2.8) becomes quite serious in SUPO which operates at a specific power of 2.4kw/liter, (HYPO was .4kw/liter), representing a hydrogen release of about 8 liter/min. Accordingly a system

was designed and installed to recombine the dissociated water and return it to the reactor. This reduced the variance in solution composition, minimized the explosive hazard and simplified the disposal of the remaining radioactive gases. The maximum pressure in the system was maintained at 3 in. of water below atmospheric to inhibit possible leakage of radioactive gases. Corrosion-resistant stainless steel 347 was used in construction. The system has operated very satisfactorly. - Refer to Fig. 11 and 12. The components function as follows:

(1) Reflux condenser condenses vapors and cools gas from 750°C to below room temperature.

(2) Steel-wool traps catches entrained liquids; slope assures their flow back to sphere.

(3) Blower maintains circulation.

(4) Catalyst chamber where recombination takes place is shown in Figure 12. The catalytic material consisted of platimum coated aluminum pellets, 1/8 in. diameter and 1/8 in. long. Thermocouples measure the temperature at different points of the catalyst bed. A progressive movement of the hot zone would indicate progressive poisoning of the catalyst by various ingredients of the gas mixture. An alternate chamber is provided in case of such poisoning.

(5) After condenser must condense 4cc of water per minute and cool gases from about 350°c to approximately 70°c.

(6) A liquid trap is located between the after and reflux condensers and is normally filled in operation without about $82cm^3$ of water.

(7) A solenoid value is actuated automatically if the pressure exceeds atmospheric thus releasing the gases to the stack. The actuating circuit also shuts the reactor down simultaneously.

3.3.8 Residual Gas Disposal

The gas disposal problem, although greatly reduced by the recombination system, is still quite prevalent. One hundred milliliters of outside air per minute is purposely allowed to leak in to keep radioactivity out of the pressure gauge lines. Nitrogen, excess oxygen, and fission product gases and vapors are released from solution. To relieve this situation, a portion of the gases circulating through the recombination system is continuously drawn off and piped underground to a 150 ft. stack atop the canyon wall where it is diluted with air and released to the atmosphere.

3.3.9 Solution Handling System

To facilitate safe handling of reactor solution samples, a special system shown in Fig. 13 was designed. A tube leads from the bottom of the sphere to a 2 liter reservoir on top of the reactor. The liquid is moved with the aid of air and vacuum lines. The probe-meter system shown gives an indication of the liquid level in the two liter reservoir. Above the reservoir is a gate valve for inserting a shielded

...posite. Below the reservoir is a shielded cart and container for removing large samples.

3.4 North Carolina State College Program

3.4.1 General

As previously mentioned, to further its nuclear engineering as well as other scientific programs, NCSC has constructed a water boiler on the campus (figures 14 through 18). At the rated level of 10KW the maximum neutron flux available in an exposure tube within the core is as follows:

Fast neutrons: 5.5×10^{11} n/cm^2-sec

Slow neutrons: 1.5×10^{11} n/cm^2-sec

3.4.2 Fuel Tank Assembly - stainless

A 1/16 in. thick 14 liter stainless steel cylinder, of length 27 cm and diameter 27.2 cm - serves as the fuel tank. Figure 15 shows 10 tubes entering the top of the tank. Only one cooling coil is shown; at the time of the drawing, three such tubes were planned, but later, four slightly shorter tubes were substituted.

3.4.3 Fuel

The tank is nearly filled with 93% enriched uranyl sulfate solution containing 860 grams of U^{235}. The choice of uranyl sulfate probably represents an improvement over HYPO and SUPO. Uranyl nitrate was used there primarily to facilitate cleaning up of the solution by ether extraction whenever necessary; experience has now shown that the need for such cleanings is extremely infrequent. A brief comparison of the two fuels was presented in section 2.1.

3.4.4 Cooling System

The four cooling coils are made of stainless steel, are 7 ft. long, and have an inner diameter of 14 in. A flow of one gallon per minute of chilled water through each coil maintains the soup temperature at about 80°C. Should a leak occur in the coils, the soup will rise and actuate a level indicator thereby tripping the safety rod and closing the valves to the cooling coil.

3.4.5 Reactor Envelope.

The cylindrical tank is surrounded by a so-called reactor envelope, made chiefly of aluminum, except for the lower portion which is of stainless steel (see Fig 16). This serves primarily as a safety device to catch leaking liquids or gases and to act as a pressure release in the event (exceedingly improbable) of an explosion. An inert gas fills the envelope and is maintained at a positive pressure to repress reactor gas leakage.

3.4.6 Reflector

The reflector is placed around the tank in the form of a 5 ft. cube. It is made chiefly of graphite bricks except for the region inside the lower portion of the reactor envelope where loose graphite powder is packed above and around the tank. The use of powder assures a path of low resistance in case of a tank explosion.

3.4.7 Catch Basin

The lower part of the reactor envelope fits into

the upper portion of a secondary catch basin. This portion of the basin is cylindrical and filled with graphite blocks; the lower portion is a broad shallow chamber. If both the fuel tank and the reactor envelope should develop leaks, the soup will collect non-critically in this lower chamber.

3.4.8 Control

Control is provided by two boron rods which project into thimbles in the fuel tank and also by cadmium shim rod which slides along the outside of the fuel tank just inside the reactor envelope. All the rods are motor driven. During operation one boron rod is poised above the tank as a safety rod. The other boron rod is partially withdrawn according to the power level desired. The shim rod is also partially withdrawn and is electronically controlled to counteract ambient fluctuations in the power level.

3.4.9 Shielding

A lead shield surrounds the reflector and filters out much of the gamma. The shielding function is performed primarily, however, by a mass of dense specially mixed concrete. Barytes (a barium ore) is used for the large particles since barium is a heavy element and thus a good absorber of gamma rays. Colemanite, a boron containing sand, was chosen as the fine aggretate since boron has a high capture cross-section for thermal neutrons and emits no secondary gammas in the capture process. The fast neutrons present are thermalized by the water which remains in the concrete.

3.4.10 Exposure Facilities

A graphite thermal column is located on one side of the reactor (see Figs. 17 and 18). It is terminated by a boron-containing shield to compensate for the lack of concrete on that side of the reactor. Eleven exposure ports thread horizontally through the concrete and/or the column. One vertical port terminates in a thimble in the fuel tank (see Fig 15). These ports are lined with steel tubes and can be plugged with concrete when not in use.

3.4.11 Gas Disposal

The gaseous efflux is processed through a recombination system similar to that employed in LUPO (Sec. 3.3.7). After the gases have passed through the catalyst bed, a few cc/min. are withdrawn, bubbled through several large water-trapped holding tanks, diluted with a large quantity of air, and then released to the atmosphere.

3.5 North American Aviation Program.*

3.5.1 General

North American Aviation has investigated several types of reactors one of which is a water boiler which rather closely resembles the Los Alamos types (see Figs. 19 and 20). The power of this water boiler as originally designed is only about one watt with a maximum flux density of 4×10^6 neutrons per square centimeter per second. The power limitation has been due largely to an inadequate means of disposing of the gaseous efflux. Recently NAA has developed

*Some information regarding this program is still classified and is not available for this report.

a recombination system similar to that of SUPO which, it is understood, provides adequate gas processing up to power levels of 50 kilowatts.

3.5.2 Core

The core of the reactor is a 12 inch diameter stainless steel sphere equipped with cooling coil and filled with about 14 liters of enriched uranyl nitrate solution (critical mass = 638 gm U^{235})

3.5.3 Reflector and Exposure Facilities

The sphere is surrounded by a graphite cylinder 5 ft. in diameter and 6 ft. high, which acts both as a reflector and as a vertical thermal column. The cylinder is composed of graphite stringers, eight of which are removable to permit experimental exposures. A "glory hole" type exposure facility lies parallel to these stringers and passes completely through the reflector and core.

3.5.4 Control

The reactivity is controlled by two safety rods, a coarse control rod, and a fine control rod, all of which pass horizontally through the reflector adjacent to the sphere. The safety rods are aluminum channel beams with boral strips, the coarse control rod is a similar channel beam with a cadmium strip, and a fine control rod is a 1 in. diameter steel pipe with a cadmium insert. The safety rods are held out by electromagnetic latches. In emergencies the latches release and weight-pulley system draws the safety rods

into the reactor.

3.5.5 Shielding

Shielding is provided primarily by concrete blocks stacked about the reactor. All blocks were smoothed and leveled so as to permit a good fit.

CHAPTER 4

HAZARDS AND SAFETY MEASURES

There are essentially two major safety problems which confront the reactor designer and later, the operating personnel. First and usually foremost of these is the radiation hazard. Second is the possibility that the chain reaction might get out of control ("runaway") and produce a "nuclear explosion". In a thermal reactor it can be shown this explosion would generally be rather mild in nature so that the primary dangers therefrom would be due to the resulting dispersal of radioactive material rather than to the force of the explosion itself. In a well designed water boiler reactor, such an explosion, as will be soon demonstrated, can not occur at all. Thus a discussion of water boiler hazards resolves itself primarily into a discussion of the ways in which dangerous radiation exposure might occur because of poor design, malfunctioning, or careless operational procedure.

4.1 Types of Radiation Hazard.

Highly lethal intensities of neutron and gamma radiations are emitted from any critical assembly of significant power level. Two types of hazards present themselves: the external type due to radiations initiated outside the body; and the internal type arising from the ingestion into the body of radioactive materials.

4.2 Origin of Reactor Radiations.

Reactor radiations arise from three sources:

(1) The fission process itself (neutrons and gammas).

(2) Decay of fission products.

(3) Induced radioactivity (by neutron capture) in experimental, structural, or other materials within the reactor.

Note that the last two sources continue to be effective after reactor operation has ceased.

4.3 Shielding

The reactor shield previously discussed normally eliminates most of the radiation hazard. Sufficient thickness must be provided to cope with all abnormally high radiation levels resulting from any conceivable malfunctioning of the reactor. Shielding (some of it portable) must be provided to cover all phases of reactor operation, e.g., loading or sampling of fuel, withdrawal of control rods, recovery and handling of exposed experimental material, etc..

4.4 Radioactivity in the Cooling System

A certain amount of radioactivity is induced in the coolant water by neutron bombardment. Most of this is usually due to capture by O^{18} forming O^{19} a gamma emitter with a 29 sec half life; this activity is rapidly reduced to negligible proportions in the water holding tanks. Some activity will also be present due to capture by dissolved substances in the local water supply. This latter activity should also be negligible after a short holding period. At least this has proved to be the case in SUPO and its

predecessors and at North Carolina State College. To establish certainty in this point, a sample of the local water supply must be tested by neutron irradiation prior to construction of the reactor. In the unlikely event that the water could not be discharged as harmless sewage after a reasonable holding period, then it might be necessary to use distilled water perhaps with a recirculating cooling system.

Monitoring devices should be placed at suitable points along the path of water flow prior to discharge into the public sewage system. Abnormal radiations should result in prompt automatic shutdown of the reactor by safety rod release and in cessation of the water flow into and out of the cooling coils. If the water flow out of the holding tank system is continuous, this should also be automatically shut off. A safer (but less convenient) design would be to release the water (during normal operation) into the sewage system at periodic intervals by positive human effort, rather than allowing it to discharge continuously.

A likely cause of an abnormal rise in the water activity would be a leak in the cooling coils. The consequences of such a leak are minimized by maintaining the pressure in the cooling coil at a higher value than that in the fuel mixture. A rise in the level of the fuel mixture then actuates a level indicator, causing a shutdown of the reactor and a sealing off of the cooling coils.

4.5 Ventilation

4.6 Ventilation

An adequate ventilation system should be installed in the reactor room so that if radioactive gas somehow makes its way into the room, it will be promptly removed. The design will be such that the air flow is from less dangerous areas toward more dangerous areas. Air monitoring equipment should be available to detect dangerous levels.

4.7 Administrative Considerations.

Carelessness alone can lead to severe radiation exposures. Standard procedures must be set up and rigidly followed for all reactor operations. Particular care must be taken in experimental or maintenance work. Appreciation of the magnitude of the hazard which exists may be gained from the fact that the maximum intensity at the surface of the North Carolina reactor from one of the exposure parts (3 in diamater) is on the order of 2000 r/sec.. It is evident that each experiment or maintenance operation <u>must</u> be carefully planned out and approved by a responsible individual; appropriate health physics instruments, shielding, danger signs, etc. must be provided. Special consideration must be given to the handling of irradiated materials, assemblies, mounts, etc. Normally experimental personnel will not be adequately familiar with reactor hazards so that close consultation with reactor personnel will be required in designing experiments. During reactor operation there should always be a qualified responsible person on hand who is encumbered with no other duties but the protection of personnel.

4.8 Abnormal Radiation Hazards

There are a number of conceivable malfunctionings of

a reactor which may lead to damage of the reactor, a temporary manyfold increase in radiation level and/or the escape of radioactive material. Proper design of the reactor will eliminate or greatly lessen the possibility of many of these and minimize their consequences if they do occur. Suitable detection and measuring devices to indicate levels of radiation, power, temperature, reproduction coefficient, and pressure should be located at critical points. These devices must be wired into the central control panel overlooking the reactor and their information presented in such a manner (meters, lights, alarms, etc.) that the operator can tell at a glance if any abnormal levels occur. The safety rods should be designed so that dangerous indications automatically cause them to be tripped, thereby shutting down the reactor. Other automatic safety devices might include dumping of the fuel solution into a non-critical catch basin, or (under certain circumstances only) shutting off of the cooling water.

4.8.1 Runaway

In designing a reactor, one must always consider the possibility of the chain reaction getting out of hand. If the reproduction factor is inadvertently allowed to exceed and remain above 1, the power level will rise steadily and, if no corrective action is taken, may cause an explosion. If the reproduction factor were allowed to exceed a value of approximately 1.01, the fuel mass would be prompt

critical (Sec 1.5.6) and the likelihood of an explosion (now more violent) would be greatly increased. Such an undesirable occurrence would not only damage the reactor, but would result in a short very intense burst of radiation, followed by the dispersal of extremely hazardous radioactive substances into the surrounding area.

One of the attractive features of the properly designed water boiler is that such an explosion can not occur. This is due to a negative temperature coefficient (Sec 2.10) and to bubbling effects. As the power level rises, the temperature increases as does also the rate of bubble formation due to the radiolytic decomposition of water (Sec. 2.10)*. Both of these increases operate to lower the reproductive coefficient, and are quite effective in preventing the power level from becoming too excessive.

Calculations have been performed (AEC document ORO-33, page 53) on the North Carolina reactor for two hypothetical cases. (1) All control and safety rods withdrawn in five seconds; (2) All rods withdrawn instantaneously. In the first case, the reproduction coefficient jumps to a maximum of about 1.006 at 2 sec. (after start of withdrawal) and then falls rapidly to 1.000 at about 5 seconds (due to bubble effect). At this point, the power level is about 400 KW and heat dissipation is inadequate. Due to the large heat capacity of the system, the temperature is just beginning to

*If the temperature were to increase sufficiently, boiling would also contribute to bubble formation.

show appreciable increase. The previously mentioned temperature effect then operates to drag k temporarily below one and the power level gradually drops off, finally settling in the neighborhood of 10KW, at which point the temperature has reached a maximum of 95°C. No great harm has been done by this sequence of events. The concrete shield is adequate to take care of the short intensified burst of radiation.

In the second case mentioned, the assembly would momentarily become prompt critical with a reproduction coefficient of 1.0157. The power would reach a peak of 10^5 KW in about 5.4×10^{-2} seconds and then rapidly drop off due to the bubble and temperature effects, finally settling at 10 KW with a maximum temperature of 95°C. Again, no great harm is done and the shield is still adequate for the intensified burst of radiation produced. Some of the fluid may froth into the space above the liquid and into the exhaust tube, but this is of no great consequence.

It should be observed that both of these cases are highly irregular and should never be encountered in practice. Proper design would normally assure that rods could never be rapidly removed and also that the safety rods would be immediately released if runaway type conditions arose.

4.8.2 Chemical Explosion

As previously brought out, one of the design

[illegible] of the [illegible] is the processing of the gaseous efflux (Sec. 2.8). To prevent formation of an explosive mixture of hydrogen and oxygen, the gases must be removed as rapidly as possible. This is efficiently accomplished by a recombination system such as that described for SUPO. Design should provide that the safety rods be automatically released if adequate flow through the recombination system is not maintained. An additional safety feature employed in the North Carolina reactor is the reactor envelope (Sec 3.4.4), which would act as a pressure relief if an explosion actually did occur.

4.8.3 Rupture of Fuel Tank

Leakage from the fuel tank could conceivably occur perhaps as a result of some sort of chemical action, an improper seal, a minor explosion, or excess pressure and temperature. Such leakage, although extremely unlikely in a proper design, would be of serious consequences and adequate provision must be made for it. Escape of the fluid could result in a severe radiation hazard, not to mention a serious economic loss, and a very painful decontamination and recovery problem. There is also the remote possibility that the fluid could collect at some point in a critical geometric configuration and thus produce a minor explosion. These difficulties can be simply avoided by providing safety catch basins beneath the reflector (previously referred to in the discussion of SUPO and North Carolina reactor).

These basins should be non-criticaly shaped and be equipped with suitable plumbing for extraction of the fluid. It must be assured of course that the fluid can not become critical while passing through reflector material enroute to the basin Leakage should make itself evident at the control panel by means of signals from level indicators in the tank, as well as by abnormal variation in the power level.

4.8.4 Earthquakes

If the water boiler is constructed in an earthquake area, provision should be made (in so far as possible) to minimize the leakage of fission products. A study should be conducted of possible methods of structurally reinforcing the concrete shield to reduce the possibilities of cracking and toppling. Drains should be provided in the floor to a holding tank beneath. The reactor room should be capable of sealing to minimize gas loss. The building of course should be earthquake proof.

4.8.5 Sabotage

The lethal nature of the core and the thickness of the concrete shield are inherent protective elements against sabotage. The reactor room should have special locks and the experimental ports should be plugged and locked when the reactor is not in use. The building should be adequately fenced and floodlighted at night. Guards should check it at intervals.

About the only conceivable method of sabotage would be to attempt to rupture the reactor with a conventional explosive. The above protection measures against earth-

quake would also be of assistance in this type of disaster.

4.9 Interlocks

To reduce the dangers of human error and carelessness it is desirable that the reactor be equipped with a system of interlocks to prevent in so far as possible any improper or unsafe sequence of operations on the part of personnel.

4.10 Safety Rods

The action of the safety rods as well as several situations which effect their release has been previously covered; however, at the risk of some repetition, it is felt desirable at this point to summarize the causes of automatic trippage. A manual trip is available at the control panel.

(1) Excessive temperature in the fuel liquid

(2) Excessive neutron flux

(3) Excessive reproduction factor, i.e., excessive rate of rise of neutron flux

(4) Abnormal liquid level in tank

(5) Excessive pressure in the tank

(6) Failure of gas recombination - circulation system

(7) Excessive temperature differential in cooling coils.

(8) Stoppage of coolant flow

(9) Excessive radiation level in coolant water to be discarded to sewage system.

(10) Excessive contamination in surrounding air

(11) Excessive radiation in stack gases

(12) Excessive radiation levels at selected critical points

(13) Electric power supply failure

(14) Interlock failure

4.11 Summarial Comment

In summary it may be said that the water boiler, with proper design and intelligent operation, is a quite safe instrument. A dangerous nuclear explosion can not occur. The problem of a hydrogen explosion has been successfully overcome by the gas recombination-circulatory system. In the very rare event that such an explosion should occur, incorporated safety features ensure that it will be mild, produce only minor damage, and not constitute a major hazard to personnel.

CHAPTER 5

UTILITY OF THE WATER BOILER AS AN EDUCATIONAL TOOL

The educational value of the water boiler stems essentially from its applicability to experimental investigation in various scientific and engineering fields. With the neutron fluxes and exposure facilities available in well designed water boilers (such as those previously discussed), the possible number of instructive and elucidative experiments is almost unlimited. Experiments performed with a research reactor, such as the water boiler, may be classified for the most part into two groups:

(1) Those which utilize the reactor to study and make use of neutron radiations and their effects upon matter.

(2) Those which utilize the reactor to study the properties of chain-reacting systems; two sub-divisions can be designated:

(a) Performance studies of the reactor itself

(b) Employment of the reactor as the external neutron source for the study of sub-critical exponential assemblies

5.1 Use of the Reactor as a Source of Neutron Radiation

Various types of radiation (e.g., α, β, γ, neutrons, etc) have been used to produce and study nuclear effects in matter. Prior to the development of the reactor, almost all of these radiations were obtained from charged particle accelerators, or from naturally radioactive materials.*

*Artificially radioactive materials were available, but on a very limited basis.

Neutron radiation was found to have properties which particularly adapted it to some types of inquiry; however, exploitation of these properties was hampered by the fact that only weak intensities of neutron radiation were obtainable. These were produced by bombardment of certain elements with other radiations from radioactive elements or from accelerators. Once the neutrons were produced, they did not easily lend themselves to control as did charged particles, so that great difficulty was experienced in trying to procure "monochromatic" beams of a desired energy which were of sufficient intensity to produce reliable experimental results.

The advent of the reactor has greatly improved this situation. Copious quantities of neutrons over a wide range of energies are available. Even if it is desired to eliminate all neutrons except those within a relatively narrow energy range, adequate numbers of them are still available to permit the detection and measurement of effects without need of exceptionally sensitive instruments. The problem of segregating neutrons of various energies, or at least distinguishing between the effects produced by neutrons of different energies in a mixed beam, has been solved only in part, there is considerable room for further research in this field. Such instruments as the mechanical velocity selector, and the fast and slow choppers, and a crystal diffraction device are currently used.

The value of the neutron as a research tool is largely due to the great readiness with which it can enter into

nuclear reactions. Since it is uncharged, it has no nuclear potential barrier to overcome, and does not suffer energy attenuation by interaction with planetary electrons.* Its ultimate fate is nearly always capture by a nucleus.** Other qualities of the neutron which are useful in certain types of investigation are its wave-like nature and its magnetic moment. For working with its wave properties, intense thermal beams are required; these can only be provided by reactors. Typical examples of the use of the reactor as a neutron source are discussed below.

5.1.1 Production of Radionuclides

A great variety of radionuclides can be produced by neutron bombardment. Many are produced by (n,α) or (n,p) reactions and are chemically separable from the targets; the great majority, however, are produced by simple capture, and attainment of a high specific activity is more difficult. The total activity produced in a thin target is governed by the following law:

$$I = \frac{\phi \sigma N}{3.7 \times 10^7} \left(1 - e^{-\frac{0.693t}{T}}\right)$$

where

I = activity in millicuries

ϕ = flux

σ = capture cross-section

* Strictly speaking, there is in actual fact a negligibly small interaction due to the magnetic moments of the neutron and electron.

** A negligibly small probability exists that a neutron will decay into a proton and electron.

N = number of target atoms

t = time irradiated

T = half life of product

Consider, for example, the irradiation of 1 gram of Co^{59} for one day in a flux of $10^{12} n/cm^2$-sec. (the order of magnitude of the flux in SUPO). Cobalt has a cross section of about 35 barns and an atomic weight of 59. Co^{60} has a half life of 5.3 years.

Then:

$$I = \frac{1}{3.7 \times 10^7}\left[10^{12}(35 \times 10^{-24})\frac{6.02 \times 10^{23}}{59}\left(1 - e^{-\frac{.693}{5.3(365)}}\right)\right]$$

$$= 3.55 \text{ mc}$$

This amount of activity is modest but quite useful for many experiments. The situation is much improved for nuclides of shorter half life as will be evident from inspection of the above formula.

5.1.2 Measurement of Cross Sections

Several methods are available for the measurement of average cross sections. One method involves inserting the sample within the reactor and noting the corresponding adjustment of the control rod necessary to maintain operation. A more refined method involves oscillation of the sample in and out of the reflector past a boron-filled ion chamber; proper interpretation of the variation in ion chamber current yields the cross section. It is also possible with the aid of a velocity selecting device to determine cross section as a function of energy. A particularly useful device is the fast chopper which is employed in the range from 10 ev to 10 Kev. It is placed

at the end of an exposure port and mechanically slices the neutron beam into 1000 bursts per second. Each burst is allowed to impinge on a scintillator which is connected to about 100 counters each operable only during a small portion of a burst. Since the time of arrival of a neutron is a function of velocity, this procedure permits count measurements for 100 different energy ranges to be taken simultaneously. Cross sections for these ranges can be determined from observation of the depressions produced in count rate measurements by the insertion of thin absorbers in the neutron beam. The fast chopper is not suited for energies below 10 ev. From 10 ev to .01 ev energy separation is best accomplished with a crystal diffraction device.

5.1.3 Study of Magnetic Structure of a Crystal by Thermal Neutron Diffraction.

The de Broglie wavelength of thermal neutrons is of the order of magnitude of the spacing between the atoms of a crystal and thus it is possible to investigate crystal structure by neutron diffraction. X ray photons have long been used for this purpose with great success; however, neutrons have the advantage that they (unlike photons) have a magnetic moment and thus their diffraction pattern will furnish information about magnetic forces within the crystal. For such a study it is desirable to employ a large thermal flux on the order of 10^{11} or 10^{12}.

The water boiler provides such a flux only in the vicinity of the core itself and thus is not especially convenient for this type of work.

5.1.4 Experiments with Neutron Mirrors

Thermal neutrons if incident at grazing angles can be reflected by very smooth surfaces. Every substance has a characteristic maximum angle of incidence in excess of which this reflection can not occur. The magnitude of this angle is a function of the nuclear-force interaction between an incident neutron and a reflecting nucleus. These angles can be determined experimentally with the aid of a well collimated thermal beam from a reactor such as the water boiler.

5.1.5 Study of Chemical Effects of Neutron Irradiation

The chemical effects of charged particle and of gamma radiations are essentially due to the ionization and orbital-electron excitation produced in the target. Neutrons do not directly produce ionization and excitation but collide with nuclei which then produce these effects. Thus the end chemical effects of neutron radiation are quite similar to those of other nuclear type radiations. Therefore, a reactor, though useful for the study of chemical effects of ionizing radiation, has no unique advantage over other investigative tools in this field. One exception must be noted. If one is studying the chemical effects arising from nuclear reactions themselves, the reactor, as a copious

source of neutrons, does have special merit. Notable among these effects is the Szilard - Chalmers reaction.

5.1.6 Study of the Effects of Radiation upon Structural Materials

In addition to the previously mentioned chemical effects of radiation there is also a group of effects important in solid materials which results from the recoil and displacement of bombarded nuclei. This disturbance of the normal crystal lattice structure of the solid manifests itself in changes of the tensile strength, electrical conductivity, thermal conductivity, elasticity, etc. of the material. A reactor with neutron fluxes comparable to those found near the core of a water boiler can be used for the study of such changes. A difficulty exists, however, in preserving the changes long enough for study. Most such changes are rapidly "erased" by normal thermal molecular activity. In order to preserve them the target must be cooled with liquified gas during and after bombardment. The accomplishment of such cooling in the interior of a water boiler near the core is not easy.

5.1.7 Study of Biological Effects of Neutrons.

The biological effects of nuclear radiation are initiated entirely by ionization. Thus the damage caused by neutron radiation is very similar to that caused by any other radiation; and, therefore, neutron radiation, although useful in biological studies, would not in most cases offer any especial advantage over other available types. It is

true that some differences in the relative biological effects of the various radiations do exist (due to differences in specific ionization), and it may be specifically desired to evaluate the effects of neutrons. In this instance a reactor might be particularly useful. Biologists, however, also employ proton accelerators for this purpose. This is permissible since the effects of neutrons upon tissue are almost (but not quite) entirely due to the ionization produced by the protons (hydrogen) with which the neutrons collide. A unique application of neutron radiation does exist, however, which deserves special mention. It is found that cancerous tissue takes up the element boron selectively. The isotope B^{10} has a high cross section (on the order of 1000 barns at .01 ev) for a (n,a) reaction. Alpha particles, because of their high specific ionization, are very potent biologically. It is thus possible to feed an experimental cancerous animal* a meal of B^{10} and produce curative effects by exposing him to neutron radiation from a reactor.

5.2 Study of Reactor Performance

The reactor itself serves as an example for the study of chain reacting systems. Typical instructional or research experiments might be:

(1) Study of control mechanism and startup and shut-down procedures

(2) Study of health physics problems

*Experiments on human beings may not be performed without express consent of the AEC.

(3) Analysis of fuel mixture and fission products

(4) Analysis of stack gases or effluent cooling water

(5) Calibration of control rods

(6) Measurement of neutron flux and of energy distribution at various points

(7) Evaluation of temperature coefficient

(8) Shielding studies

5.3 Employment of the Reactor to Operate Sub-Critical Exponential Assemblies

Much can be learned about proposed critical assemblies by operating sub-critical models (dimensions about 1/3 of those proposed) exponentially, using the reactor as the necessary external neutron source. From a study of the thermal flux distribution, it is possible to accurately estimate the critical dimentions.

5.8 Design Criteria Peculiar to an Experimental Reactor

It is desirable that an experimental reactor be a relatively small modest scale device, and yet have the highest possible thermal and fast neutron flux. It will be shown that the water boiler design is of considerable merit in all these respects. Other desirable features of an experimental reactor, which are present in the water boiler are safety, low cost, and adequate exposure facilities; these items are discussed elsewhere in this paper.

5.4.1 Maximizing of Thermal Neutron Flux

The equilibrium thermal flux in a reactor obeys the following law:

$N\sigma_f \phi_{th}$

or $\phi \sim P/N \sim$ power per kilogram U^{235}

where

$P =$ power/unit volume

$F =$ fissions per second per unit volume

$N =$ no U^{235} atoms / unit volume

$\sigma_f =$ thermal fission cross section of U^{235} atom

$\phi_{th} =$ thermal neutron flux

Thus to maximize the thermal flux one must maximize the power output per kilogram of U^{235}. The power output of a water boiler is limited by the rate of heat dissipation and gas disposal (Sec. 2.11).

The gas disposal limitation is greatly reduced by the recombination system previously discussed. The problem of heat elimination, which is characteristic of all reactors, is greatly facilitated in the water boiler. The homogeneous liquid nature of the active material permits a rapid rate of heat transfer between the fuel and moderator (effectively instantaneous) and between the fuel-moderator mixture and the cooling coils.

5.4.2 Maximizing of Fast Neutron Flux and Reduction of Physical Size

The uncollided neutron flux is given by the following:

$$\phi_0 \Sigma_s = q \sim P$$

or

$$\phi_0 \sim P/\Sigma_s$$

where

$\phi_0 =$ uncollided neutron flux

$\Sigma_s =$ macroscopic scattering cross section

$q =$ number of neutrons produced per sec. per unit volume

P = power/unit volume

At high energy Es is rather insensitive to the kind of moderator; thus the uncollided flux is proportional to the power per unit volume. Therefore, to achieve maximum fast neutron flux, it is necessary to reduce the volume to as low a value as possible. The water boiler design permits the use of a small volume by employing highly enriched fuel and a hydrogen-containing moderator (water). The use of enriched fuel eliminates most of the neutron-robbing U^{238}, thereby reducing the amount of U^{235} (as well as total uranium) required for criticality and permitting the use of the water moderator.*

As pointed out earlier, neutrons lose energy in collisions with atoms of hydrogen more rapidly than with atoms of any other element; thus a relatively small amount of moderating material is required to "thermalize" the neutrons. Furthermore, rapid thermalization tends to reduce the probability of neutron losses due to leakage and capture and thus has the effect of further reducing the mass of U^{235} required for criticality.

Because of these principles, criticality is achieved in the typical water boiler with appreciably less than 1 kilogram of U^{235} in a core of dimensions on the order of only one foot. Yet the water boiler is operated at power levels on the order of 10 kilowatts or more and has neutron flux levels comparable to those observed in the much larger

*Hydrogen (i.e. H^1) cannot be used to moderate a natural uranium reactor, since the effect of its small but significant neutron capture cross-section when added to the effect of the U^{235} capture is sufficient to deny the possibility of a chain reaction.

graphite reactors at Oak Ridge or Harwell. To obtain criticality in a natural uranium reactor, two tons of uranium and a comparable amount of graphite or heavy water as required.

It might be noted at this point that a reactor of large volume does have a few advantages over one of small volume. Generally a greater number of experimental samples can be simultaneously irradiated. Also, the insertion of a sample in one part of the reactor will not as greatly affect the flux present at another part.

CHAPTER 6

MISCELLANEOUS ADMINISTRATIVE CONSIDERATIONS

6.1 AEC Policy on Research Reactors

During World War II and for several years thereafter, nearly all investigation and use of research reactors was confined to the Atomic Energy Commission and their contractually affiliated organizations.

Such a policy was almost a necessity in view of stringent security regulations and the early stage of development of reactor technology. In recent years, however, this policy has undergone considerable change. A large amount of information on several relatively safe low cost reactors of simple design has been declassified and released to the public. Research and educational organizations have pressed for permission to construct their own reactors.

The AEC now recognizes the values of allowing independent groups to conduct their own reactor research and training, subject to regulatory action by the AEC, only with regard to matters of security, safety, and the control, manufacture and safeguarding of fissionable material. Pioneer negotations with AEC were made by North Carolina State College and eventually led to the construction of their present reactor. Other organizations have taken similar steps. These organizations pay all costs except that of the fissionable material which is loaned by the AEC.

6.1.1 Negotiations for Reactor Construction

An organization desiring to construct a reactor must first make a study contract with AEC. It then renders a report which includes the design, a study of the hazards, an operational plan, and security measures. Further discussions occur and the AEC then makes an evaluation of the project on the basis of the following criteria:

a) Financial adequacy

b) Qualifications of responsible personnel

c) Merits of research and training program to be undertaken

d) Fulfillment of AEC requirements with regard to amount of fissionable material, security, classification, accountability, health, and safety

6.1.2 Loan of Fuel

All fissionable material is owned by the AEC unless transferred to the military by Presidential directive. The AEC will loan and reprocess all fuel as needed. Such fuel is subject to recall in the event of emergency or if the AEC should become dissatisfied with the standards or methods of the using organization. A loan of one kilogram or more of fissionable material requires the presence of a resident AEC custodian.*

*The water boiler reactors discussed in section 3 all use less than 1 kilogram.

6.1.3 Security

The director of the reactor project and preferably several other supervisory personnel as well should possess an AEC "Q" clearance and be thoroughly conversant with all security regulations. The director will be responsible for the safe guarding of all classified material. He should be able to recognize any classified information that may be encountered in the course of a classified or even an unclassified investigation. Such information should be promptly declared as classified pending consultation with the AEC.

6.2 Initial Cost of Water Boiler

The cost of HYPO, SUPO, and the North Carolina water boiler was each about $500,000. The cost of the North American one-watt boiler is from $75,000 to $100,000. A higher power model because of the necessity for more elaborate systems of cooling, gas handling, and shielding, would cost considerably more.

6.3 Housing

It is desirable that the water boiler be housed in a building separate from other activities not closely related to its operation. The reactor room should be sufficiently large to allow comfortable use of all research facilities. It should have adequate emergency exits and be capable of sealing to prevent appreciable excape of radioactive gases in the event of leakage.

Adequate auxilliary facilities should be placed close to the reactor, preferably in the same building. These would

include the necessary physical, chemical and instrument laboratories plus store rooms and decontamination room. Access should be provided to any underground gas or water holding tanks. One rather elaborate layout suggested during the North Carolina proposal is shown in Fig. 21 (AEC document ORO 33).

6.4 Staff

It would seem imperative that at least one and preferably two persons on the PhD level should be available who have had first hand experience in the operation of nuclear reactors, who are qualified to perform any necessary calculations, and who are thoroughly grounded in the pertinent principles and procedures of health physics. One of these men would act as director of the project and would assume complete responsibility for reactor operation and safety, planning and supervision of the experimental program, and the necessary training of operating and research personnel. Both men, though perhaps completely preoccupied with the reactor in its very early stages of operation, would not thereafter be expected to devote their complete time to reactor problems. It is felt that most of their duties could be delegated to a full time assistant, a man of perhaps Master's Degree Level, who could supervise all routine operations, and conduct much of the necessary liaison with persons or groups desiring to use the reactor research facilities.

In addition to the above personnel, there should be avail-

able a number of qualified maintenance, health physics and laboratory technicians, plus a locally trained pool of operators. Also, scientists and engineers of various fields should be at hand for consultation on special problems.

All personnel who are concerned with operating, maintaining or conducting research with the reactor should receive complete training in reactor hazards and safety procedures prior to being allowed to approach the reactor.

6.5 Maintenance

Maintenance problems do not appear to be excessive. Regular checks should be made of the cooling system, gas recombination system, gas disposal system, instruments, gauges, control panel, rod mechanisms, health physics, devices and ventilation systems. Particular attention must be paid to the calibration of the measuring devices. Minor decontamination problems may arise during research operations.

CHAPTER 7

CONCLUDING REMARKS

In the last six chapters an effort has been made to give a clear explanation of the water boiler reactor, its possible dangers, its utility, and the problems associated with acquiring and running it. Before closing, it would seem of merit to restate in concise form some of the more important points covered.

7.1 Summary of Advantages of the Water Boiler

(1) The water boiler is a time tested device. Ten years of experience and satisfactory operation at Los Alamos have proven it to be a safe, reliable, and highly useful experimental tool. The feasibility of its installation at an educational institution and of its employment in an academic curriculum is being convincingly demonstrated at North Carolina State College.

(2) Although a small scale reactor, it provides relatively high fast and slow neutron fluxes at moderate power level.

(3) In a proper water boiler design, a runaway nuclear explosion is impossible because of the negative temperature coefficient and because of the "bubble effect" (drop in reactivity of the solution due to appearance of bubbles arising from the radiolytic decomposition of water).

(4) The cost of a good water boiler is quite moderate

(on the order of \$500,000).

(5) The liquid form of the fuel-moderator material is quite convenient for such operations as loading and bringing to criticality, sampling, unloading, purification, analysis, etc. The use of liquid also simplifies heat transfer problems in the design.

(6) The construction of a water boiler is relatively simple in comparison to other reactors.

(7) The large concrete shield, normally present in the water boiler, is an effective protection against sabotage, as well as radiation.

(8) Less than one kilogram of U^{235} is required to operate the water boiler; present AEC regulations would require a resident custodian if the quantity were one kilogram or greater.

7.2 Summary of Disadvantages of the Water Boiler:

(1) An explosion hazard is created by the radiolytic decomposition of the water moderator. The installation of a recombination system plus other safety features, however, can eliminate this threat.

(2) There exists a problem of radioactive gas disposal which is aggravated by the flushing action of the afore-mentioned radiolytic decomposition of water. A recombination system, together with a suitably designed disposal system for the residual gases, can successfully deal with this problem.

(3) Since the fuel is of a liquid nature there always exists the finite possibility of leakage. The occurrence of such leakage and the consequent liberation of fission products could constitute a severe hazard. It is felt, however, that the safety features employed to avoid this contingency are thoroughly adequate. These include one or more catch receptacles beneath the fuel tank, plus various protective measures against sabotage, earthquake, and nuclear or chemical explosion.

7.3 Comparison of Water Boilers

Some of the features of the water boilers discussed in this report are summarized in the following table:

WATER BOILER CHARACTERISTICS

Reactor	Date	Mass of U^{235} in gm.	Fuel Compound	Thermal Flux n/cm^2-sec.	Power KW	Cost in\$ $x10^6$
LOPO	1944	575	UO_2SO_4	-	$5x10^{-5}$	-
HYPO	1944	870	$UO_2(NO_3)_2$	10"	16	.5
SUPO	1951	870	$UO_2(NO_3)_2$	$1.7x10^{12}$	45	.5
NCSC	1953	860	UO_2SO_4	$1.5x10^{11}$	10	.5
NAA*	1952	638	$UO_2(NO_3)_2$	~ 10[illegible]	10^{-3}	.075-.100

7.4 Future of the Water Boiler

At least two additional institutions, the University of Utah and the U.C.L.A. medical school, have tentatively planned to construct water boilers. It seems likely that this trend will continue and that within a few years, a number of these

*It is understood that North American has modified its water boiler and is now operating at a power level of 50 KW. Data for this unit are not available.

units will be in operation at various universities and laboratories about the country.

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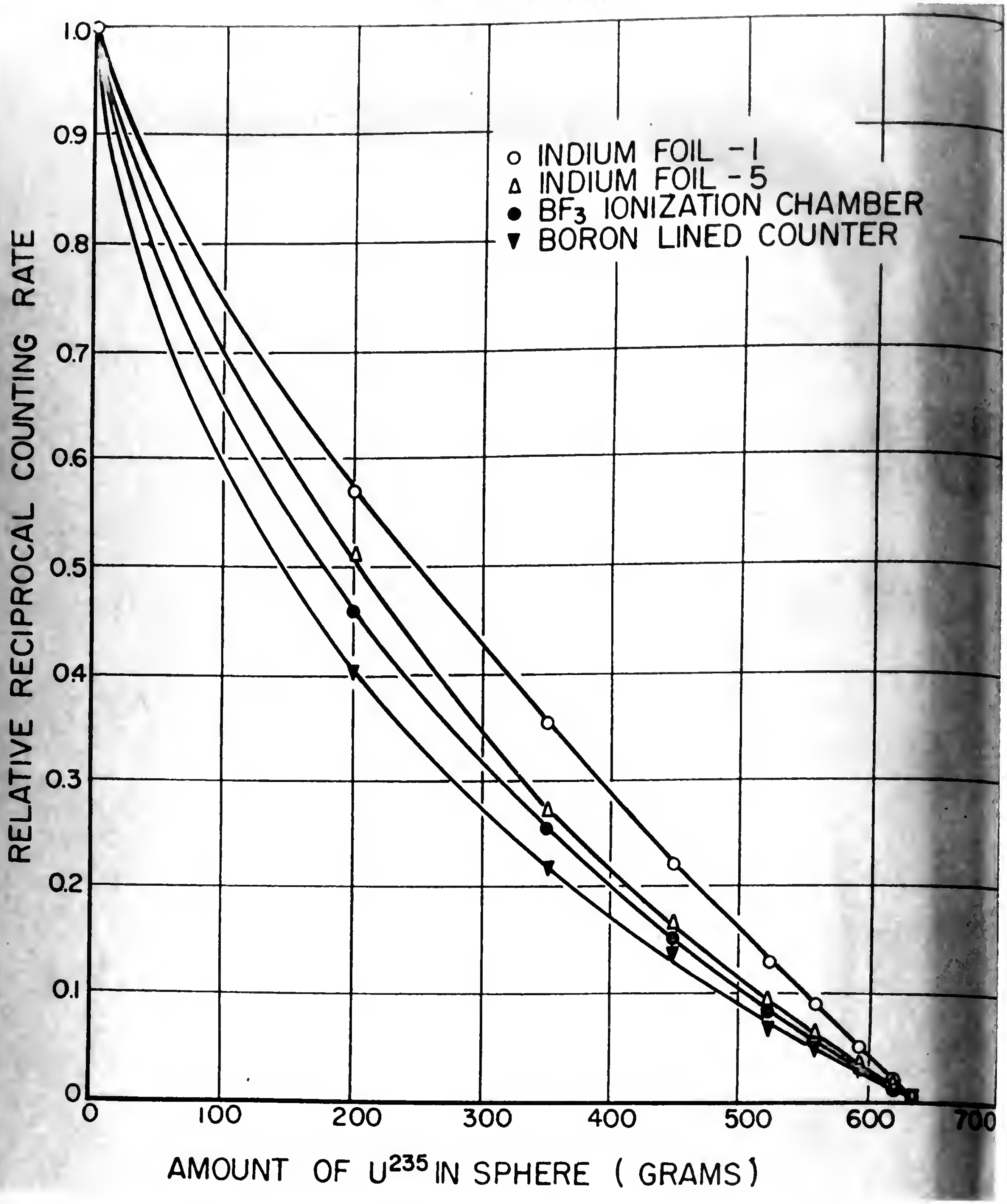


Figure 1.

Plot of reciprocal counting rate as a function of the mass of U^{235} during the initial approach to criticality

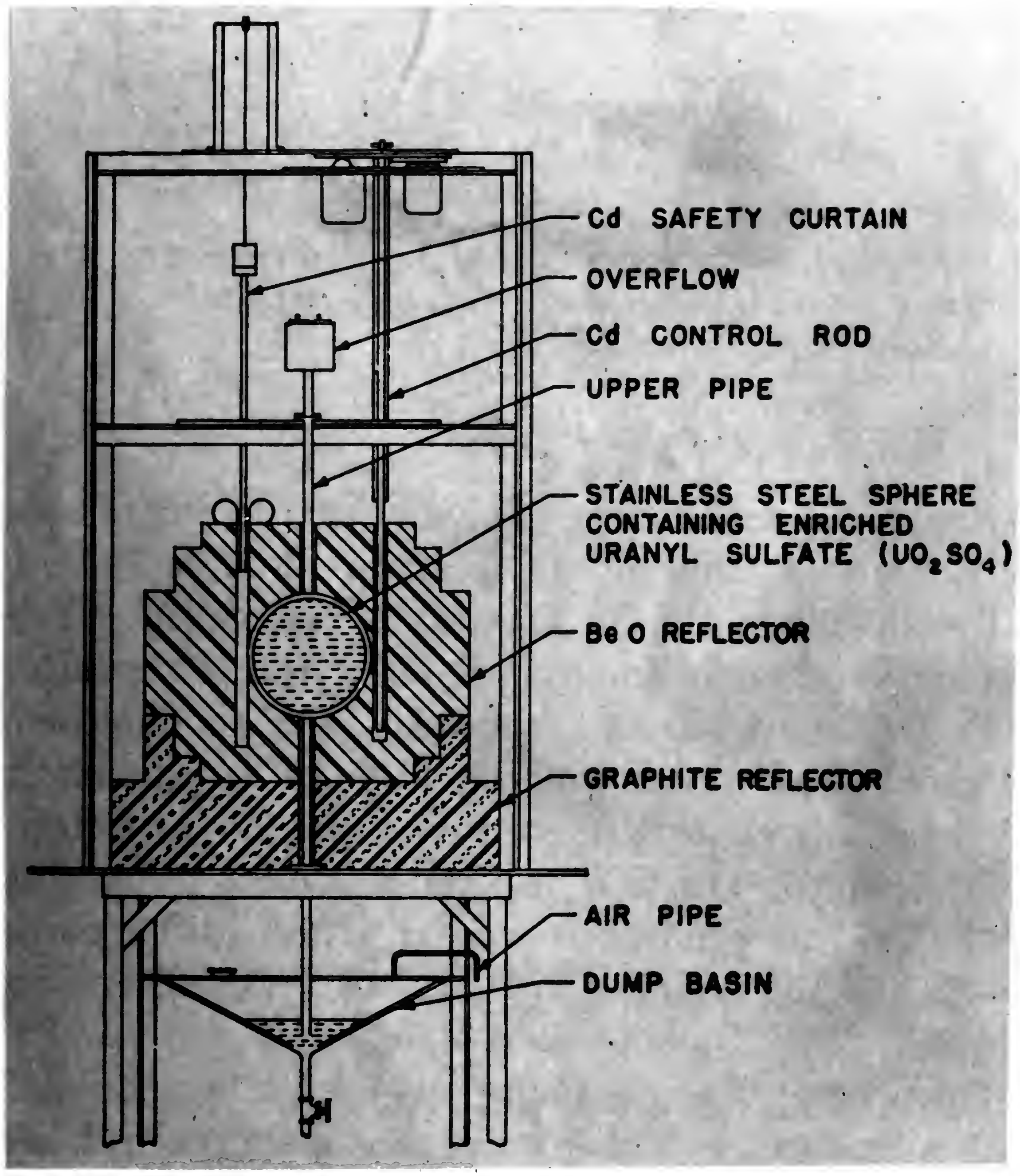


Figure 2.

Diagram of LOPO

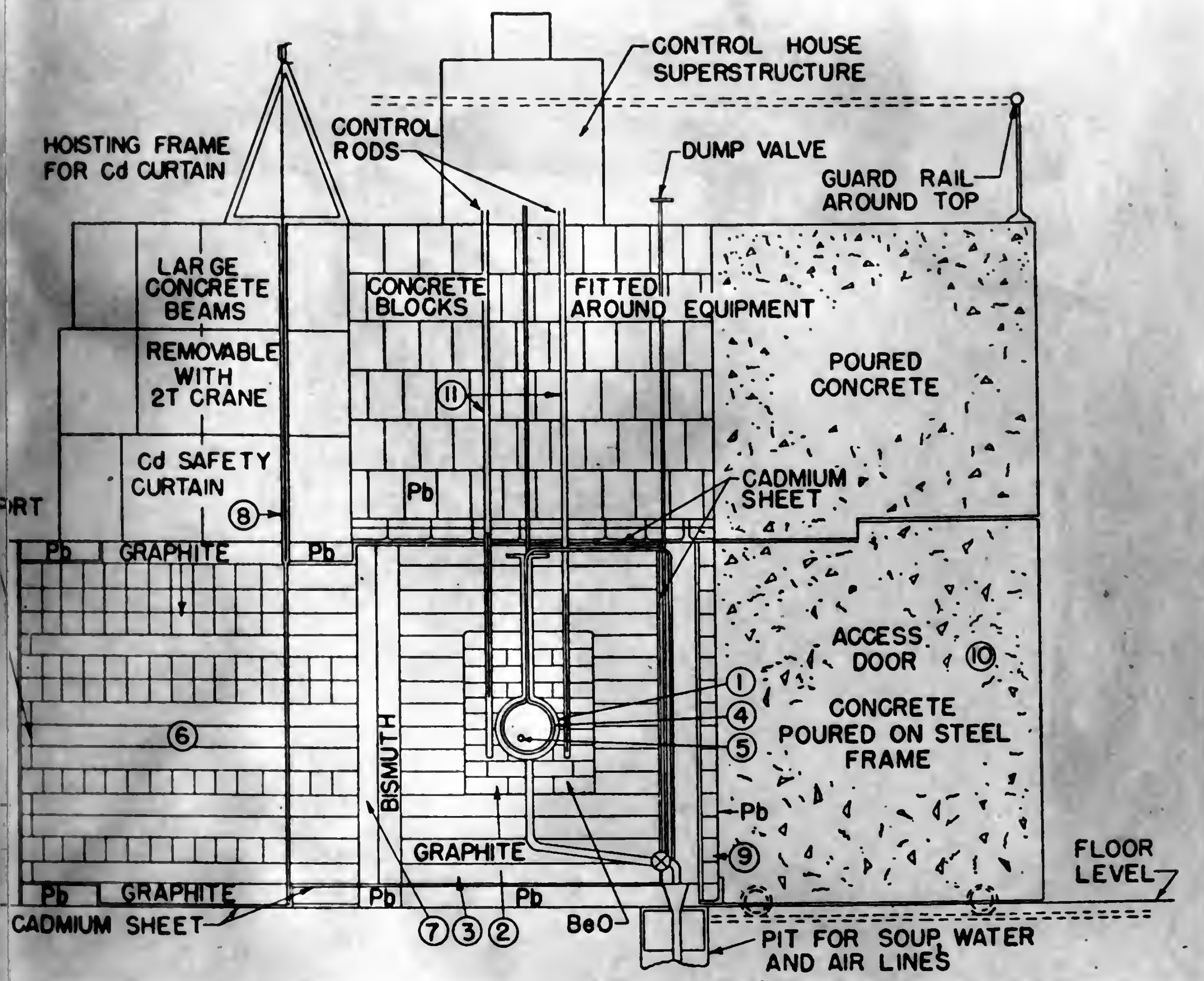


Figure 3.

Diagram of HYPO

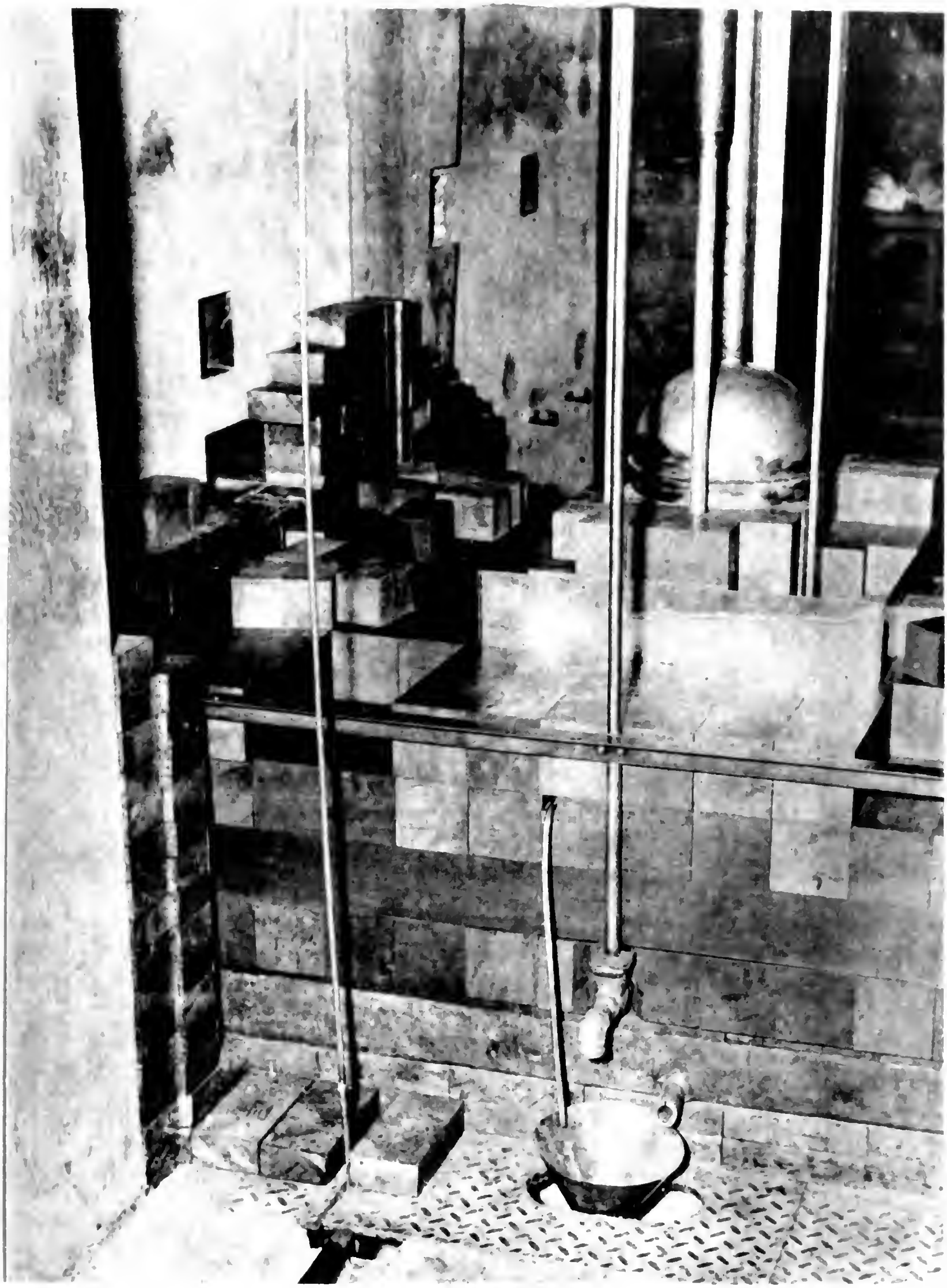


Figure 4
Interior view of HYPO showing sphere, reflector and drip pan

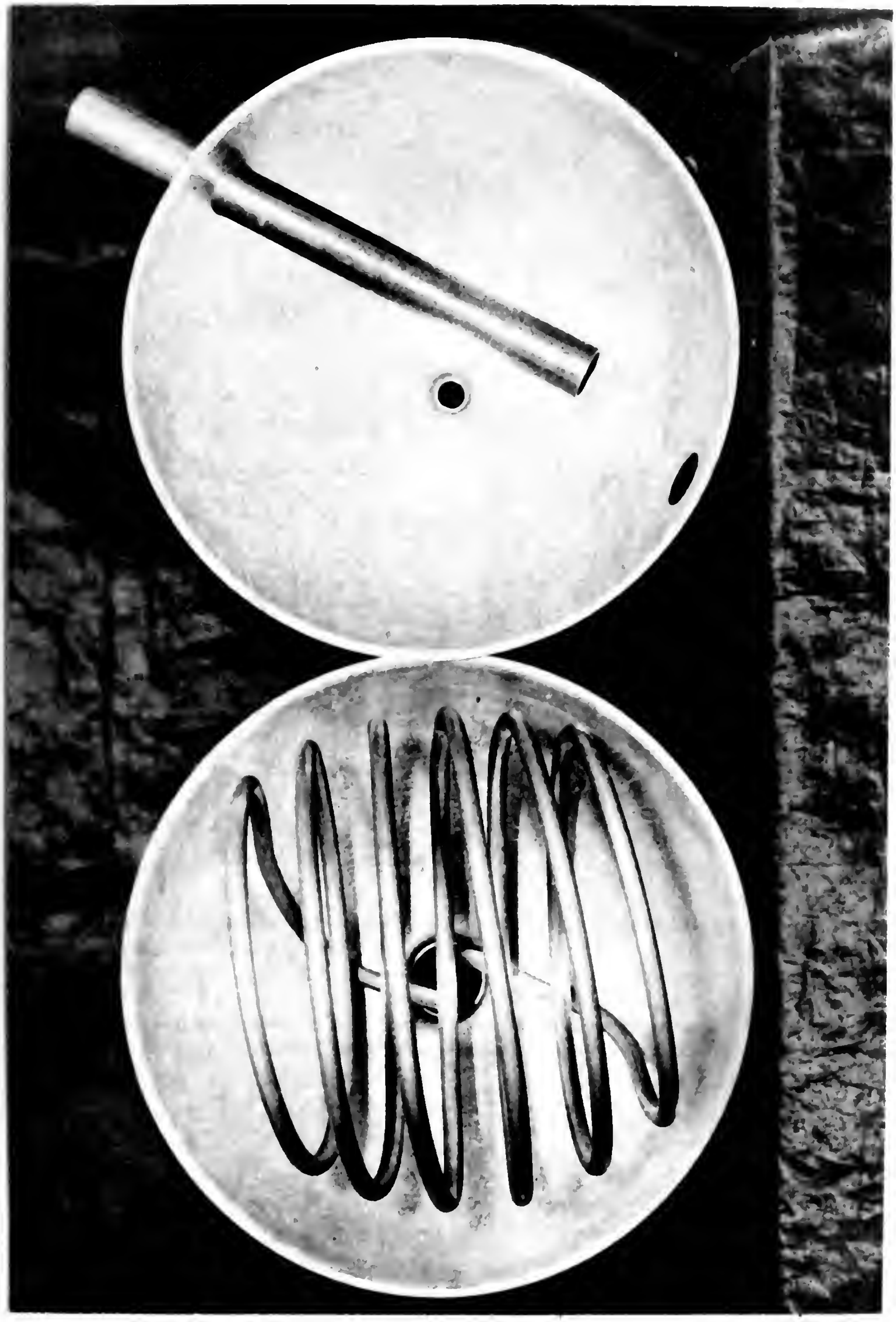


Figure 5.
Cooling coil HYPO

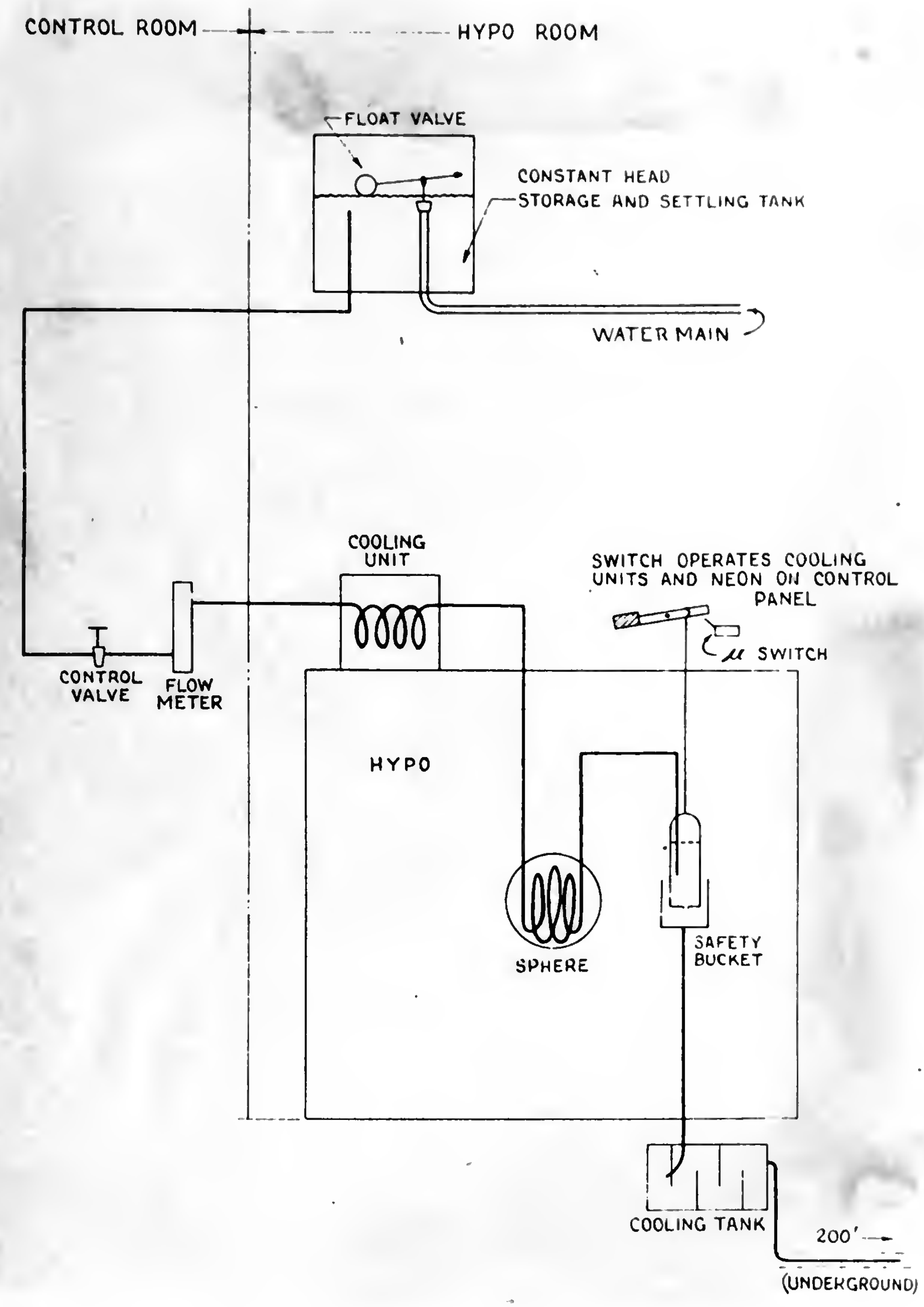


Figure 6.

Water Cooling System

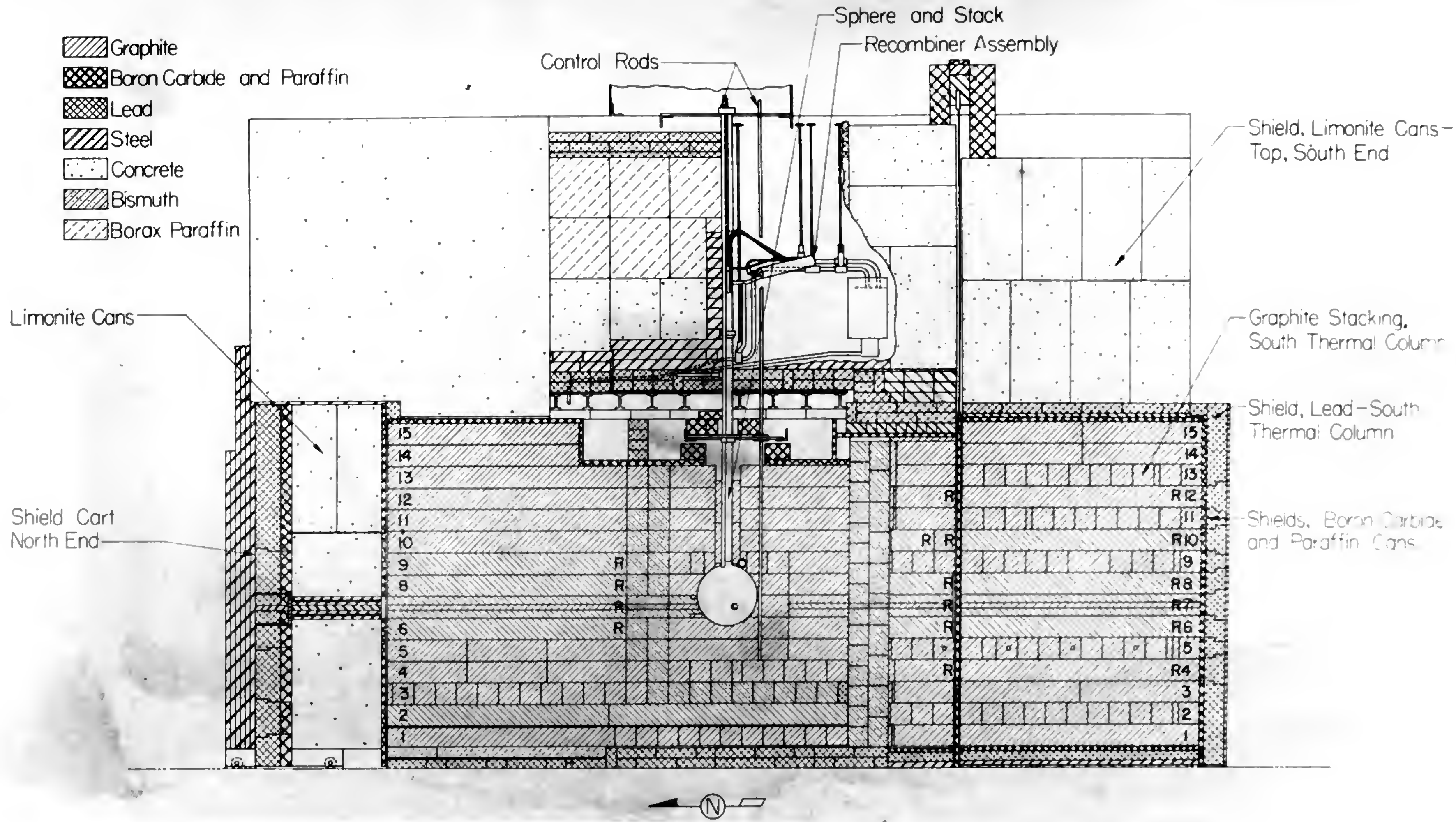


Figure 7.
North-south vertical section of SUPO

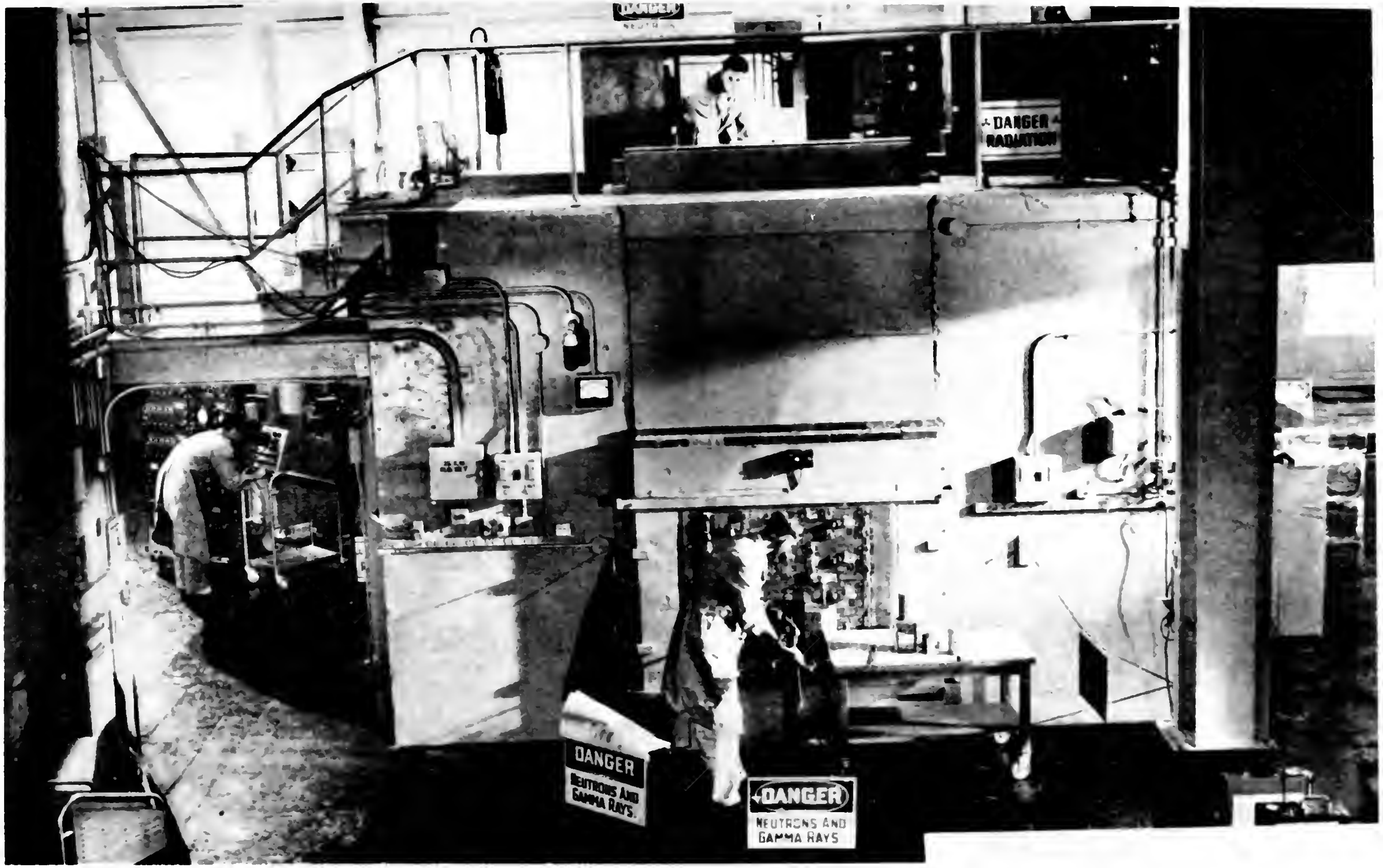


Figure 8.
South face of SUPO

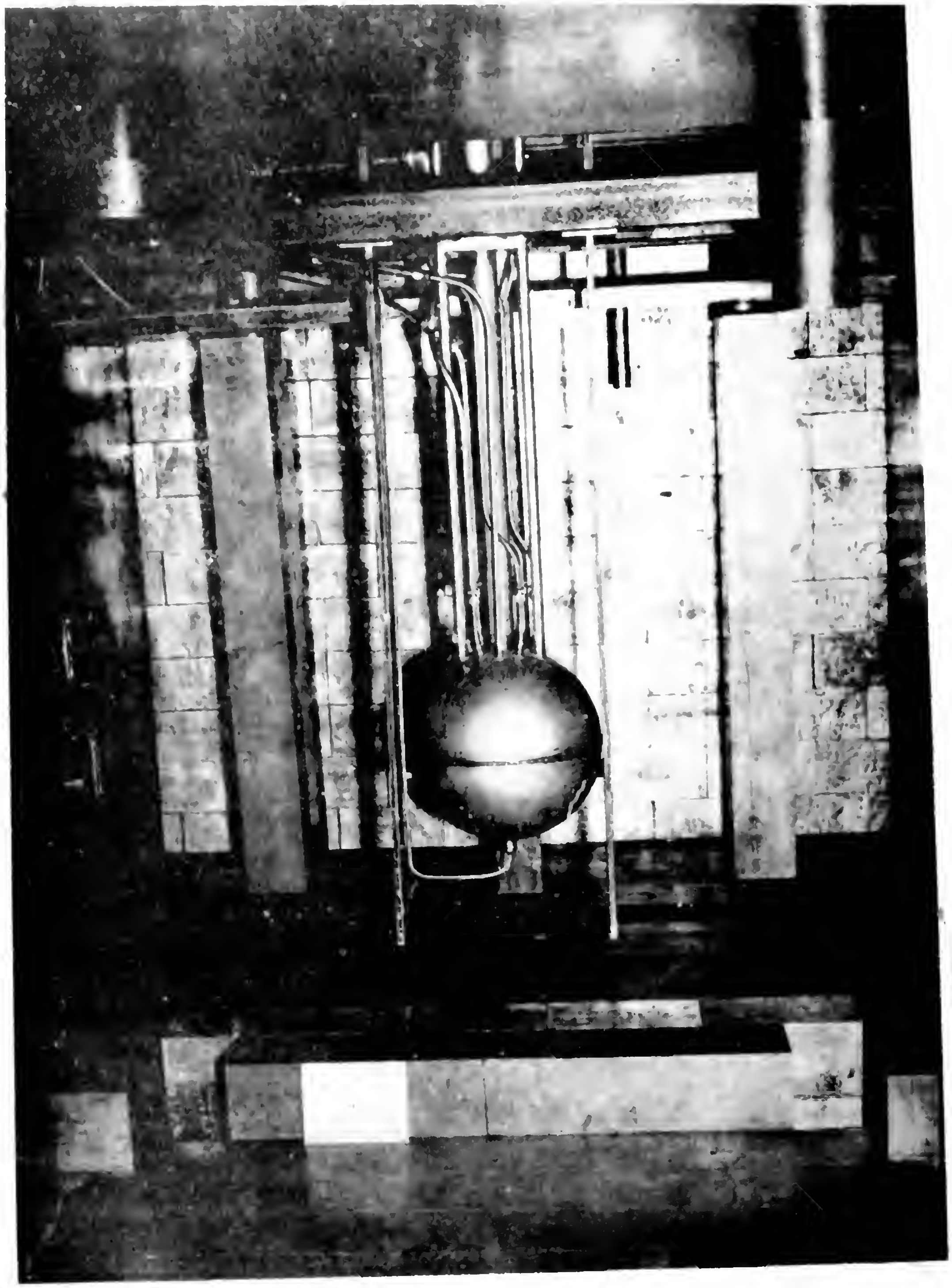


Figure 9.

Interior view of SUPO showing reflector and sphere

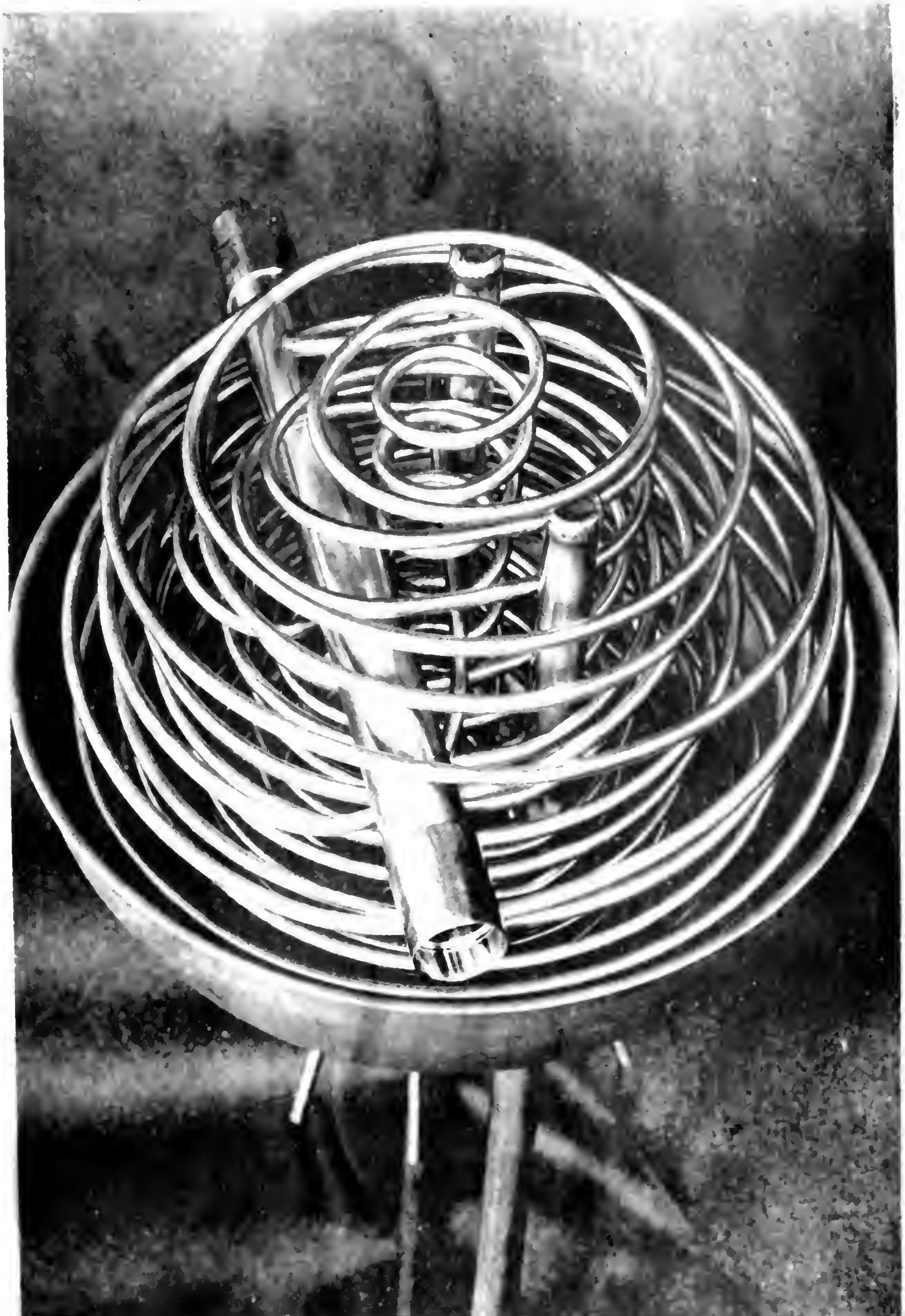
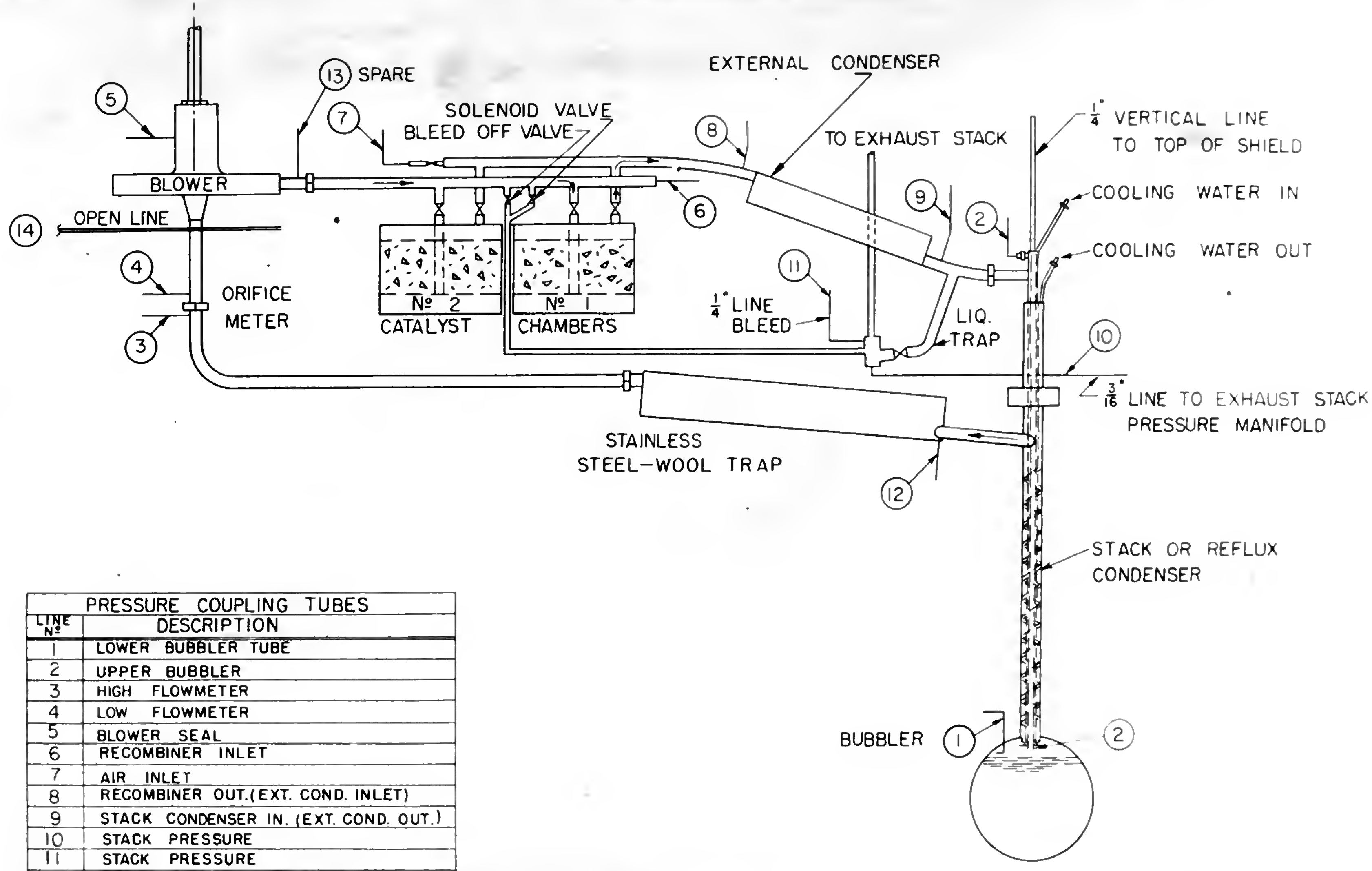


Figure 10.

Internal assembly of sphere, SUPO



PRESSURE COUPLING TUBES	
LINE №	DESCRIPTION
1	LOWER BUBBLER TUBE
2	UPPER BUBBLER
3	HIGH FLOWMETER
4	LOW FLOWMETER
5	BLOWER SEAL
6	RECOMBINER INLET
7	AIR INLET
8	RECOMBINER OUT.(EXT. COND. INLET)
9	STACK CONDENSER IN. (EXT. COND. OUT.)
10	STACK PRESSURE
11	STACK PRESSURE
12	STACK CONDENSER OUT.
13	SPARE (PLUGGED)
14	LEAK DETECTOR - COPPER TUBE

Figure 11.

Recombination assembly, SUPO

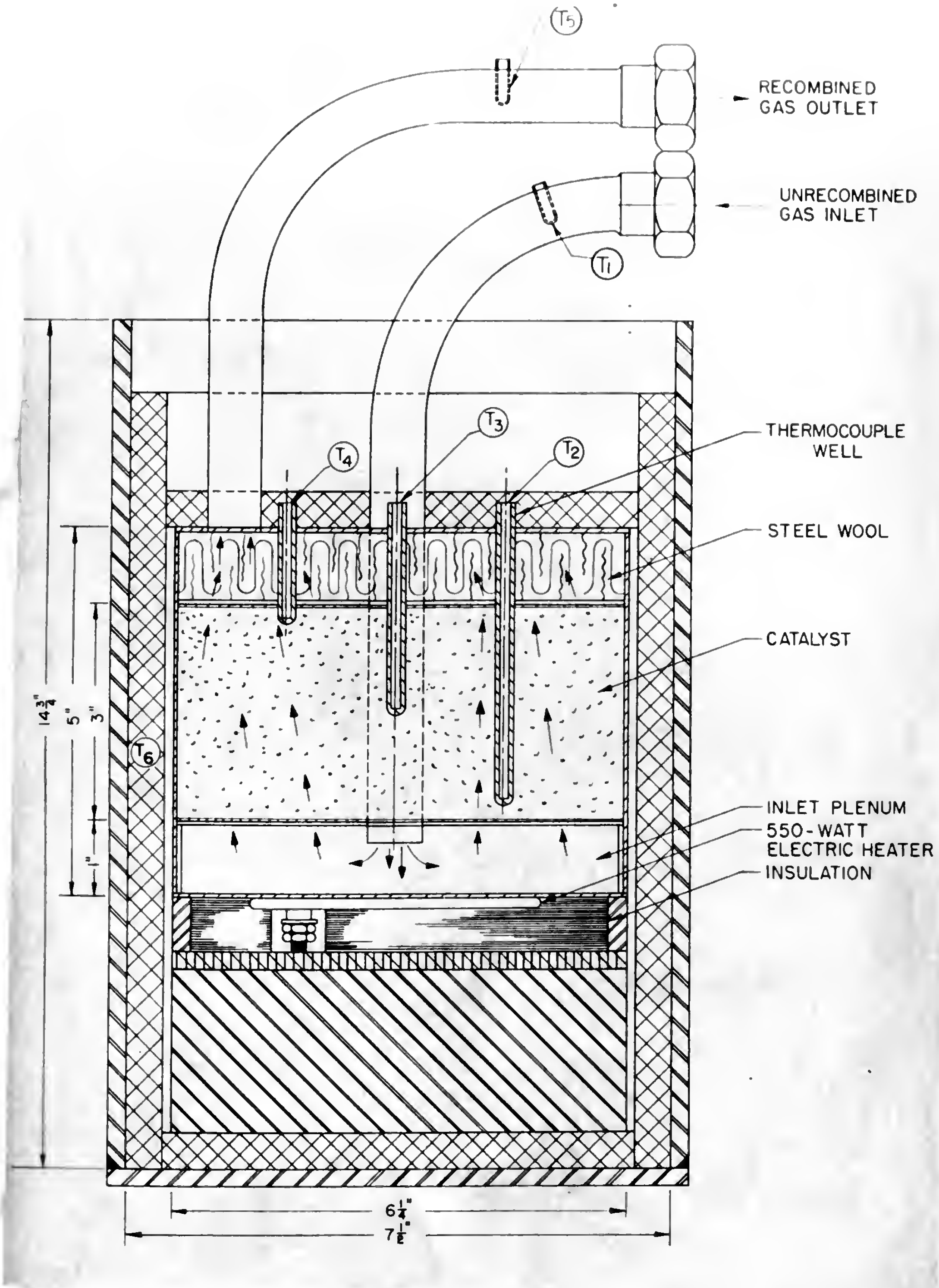


Figure 12.

Catalyst chamber of recombination assembly, SUPO

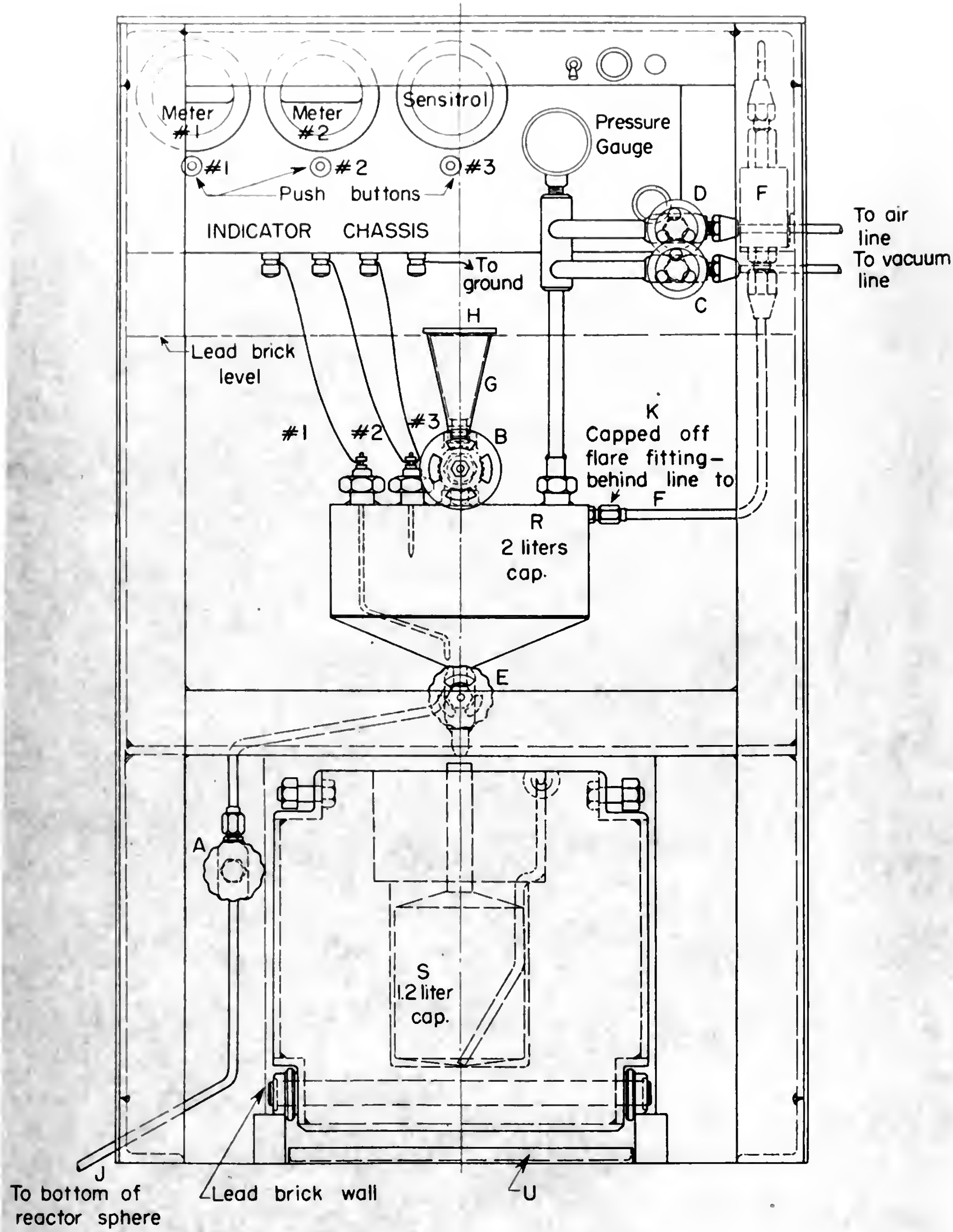


Figure 13.

Solution handling system, SUPO

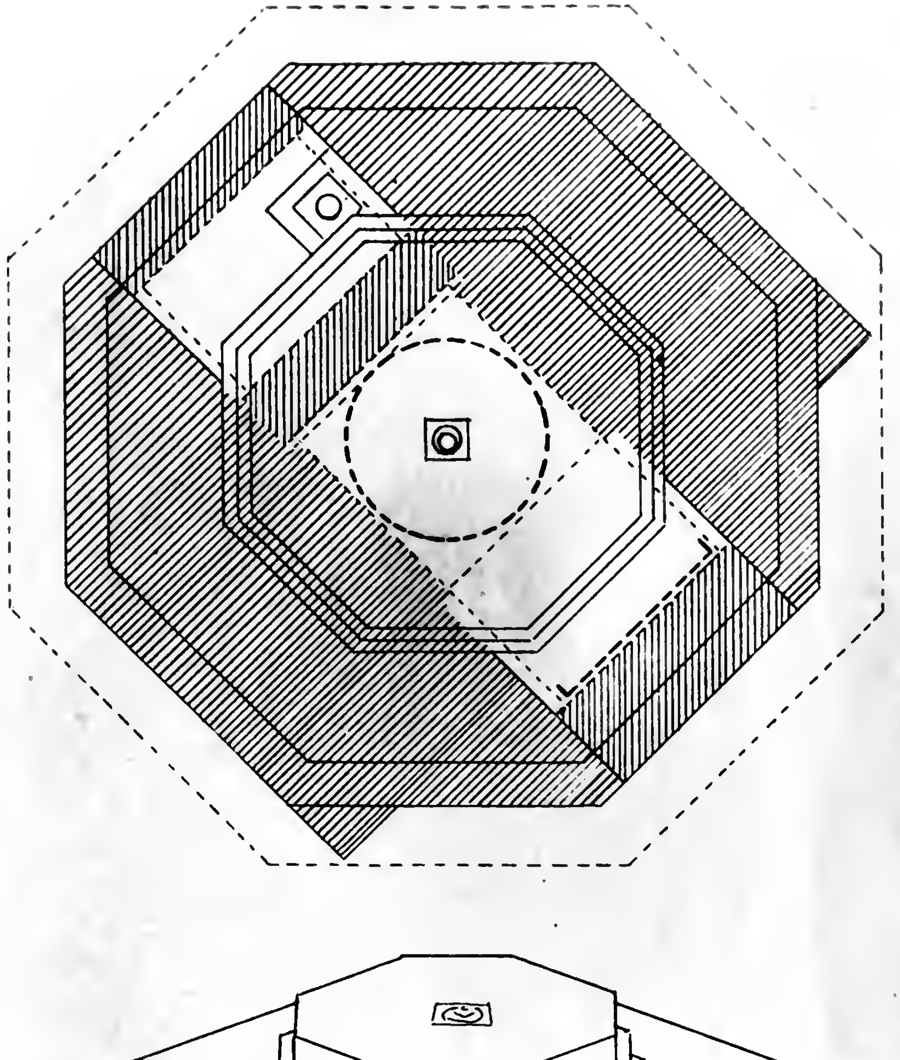


Figure 14.

Shielding assembly of the North Carolina reactor

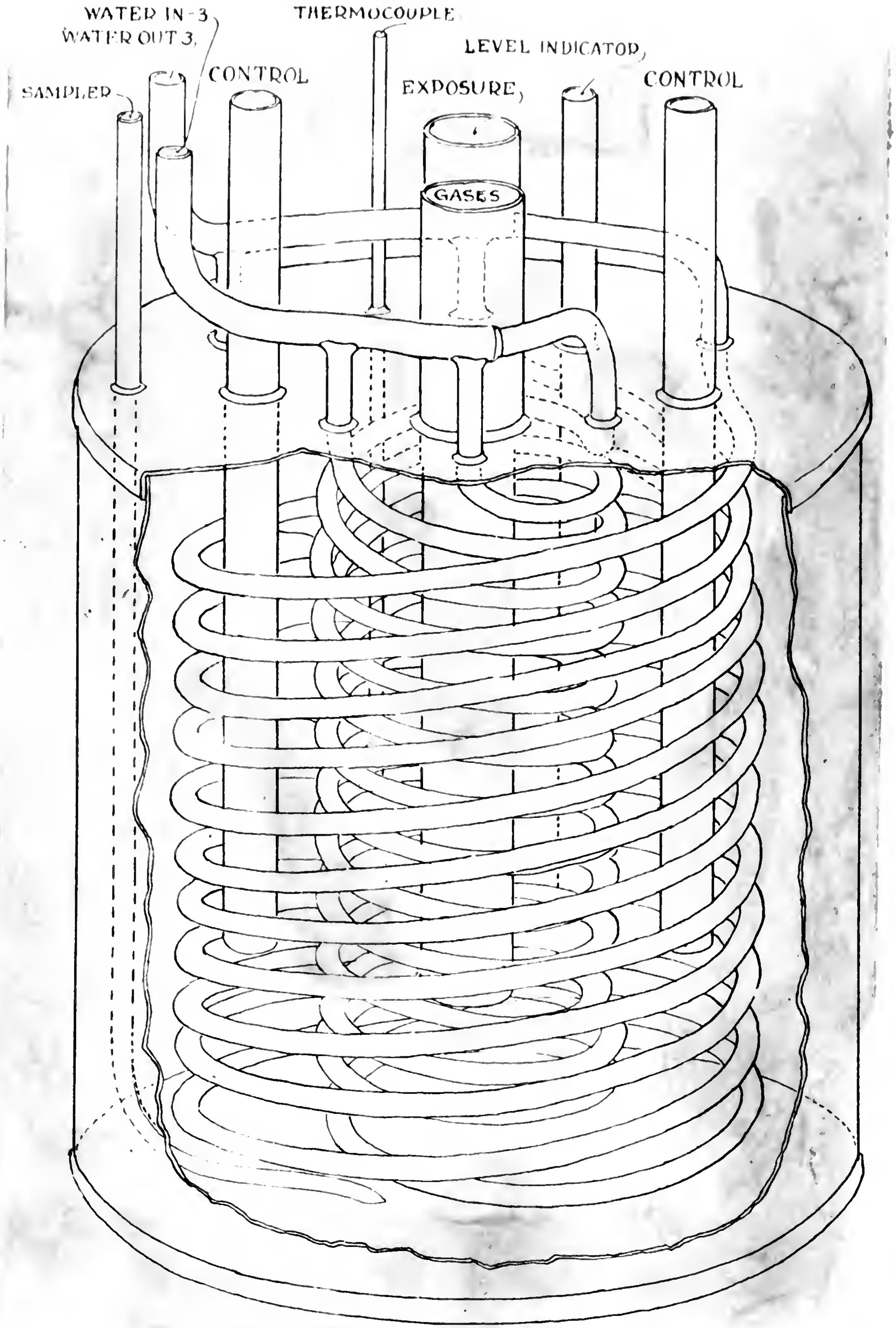


Figure 15.
Fuel tank assembly, North Carolina reactor

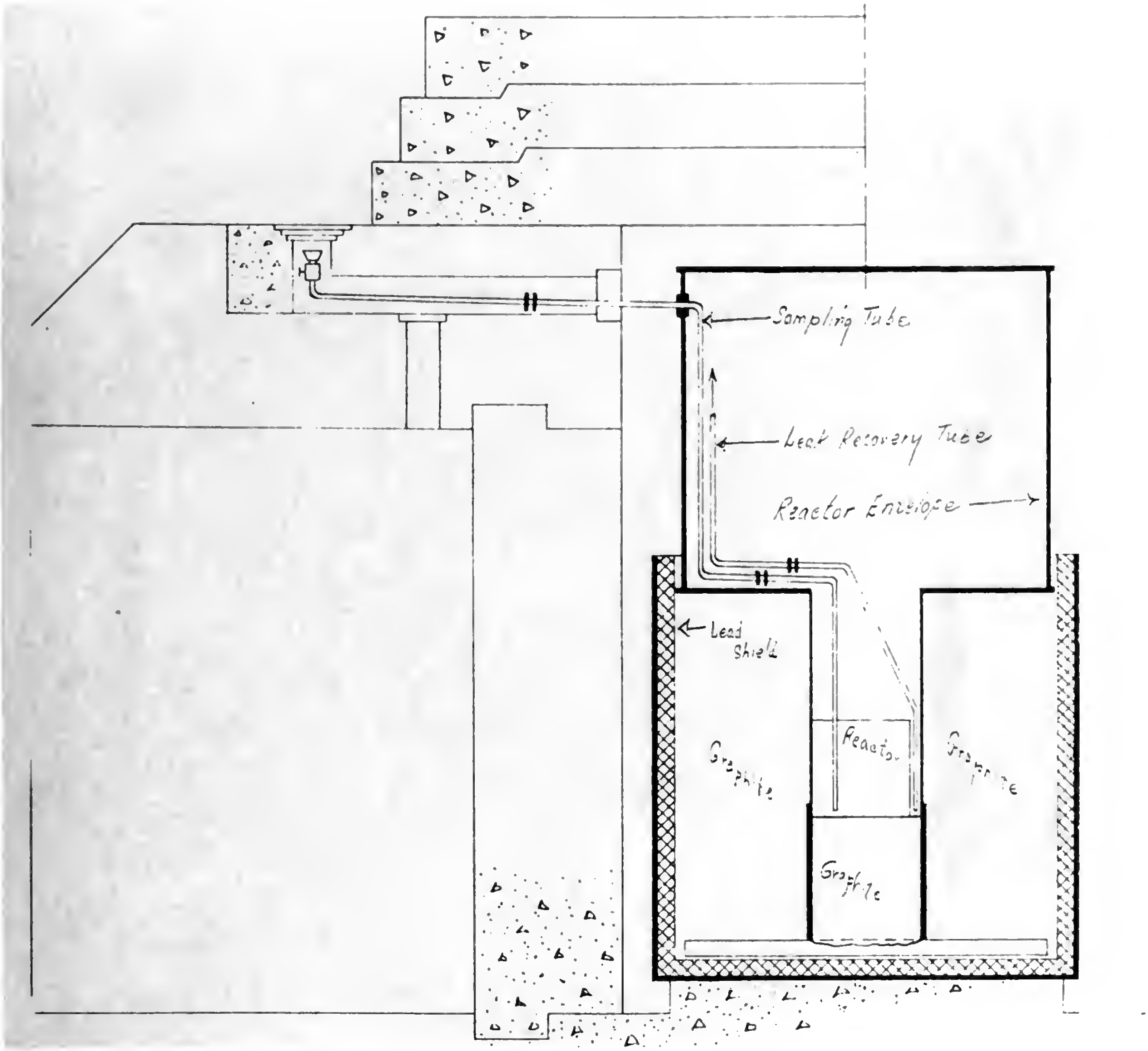


Figure 16.

Reactor envelope and sampling tube, North Carolina reactor

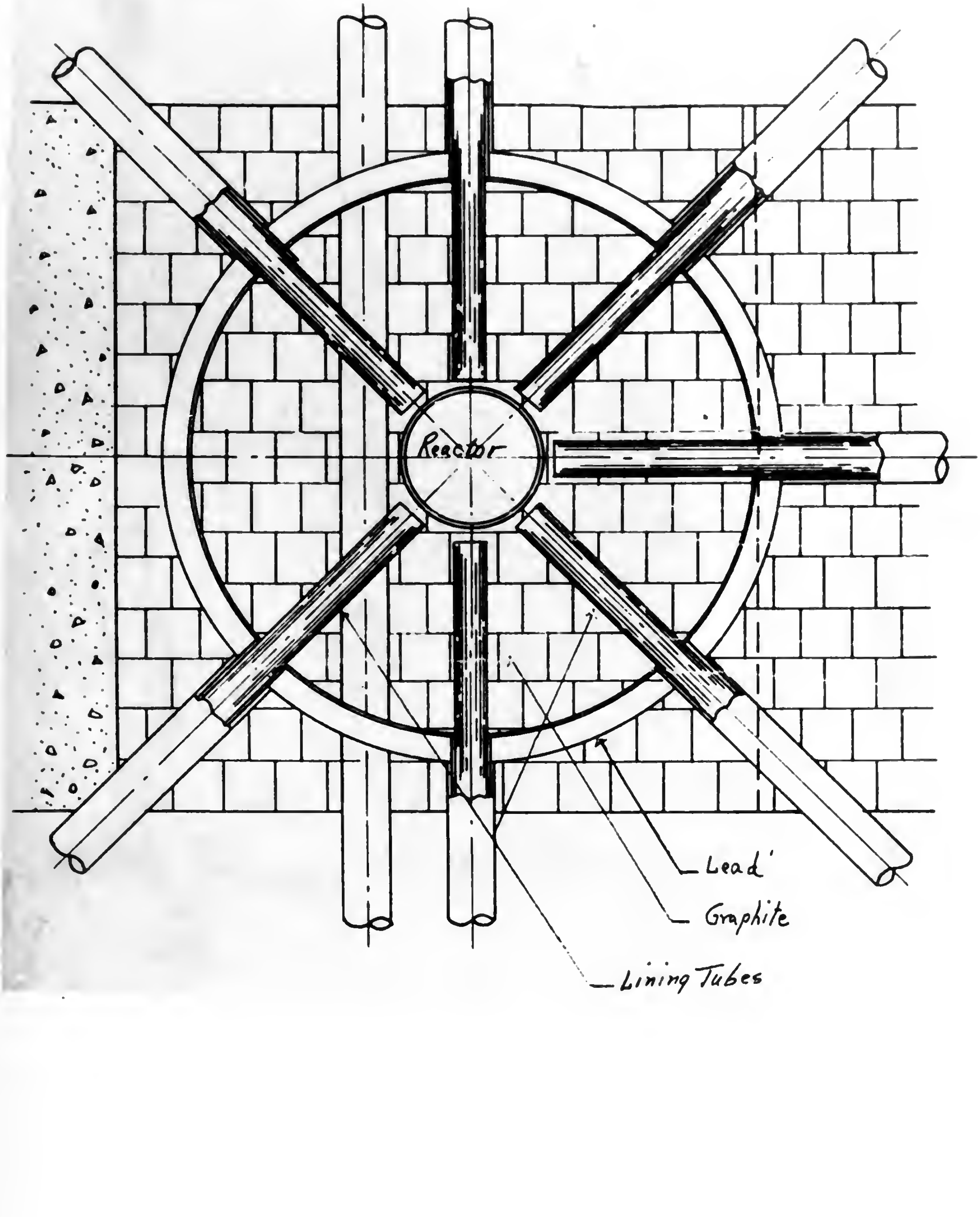


Figure 17.

Cross section showing exposure ports

North Carolina reactor

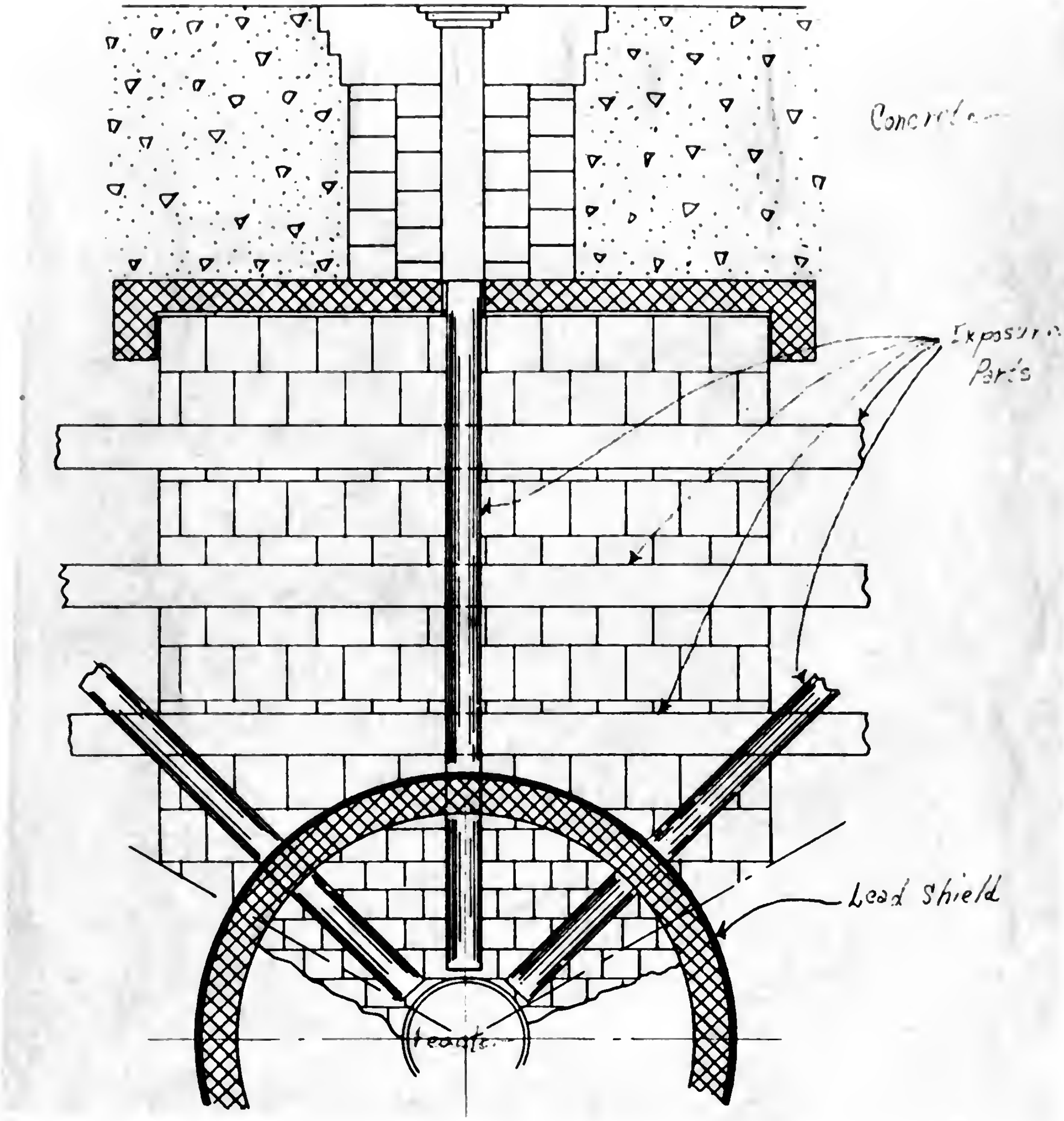


Figure 18.

Cross Section showing exposure ports and thermal column,

North Carolina reactor

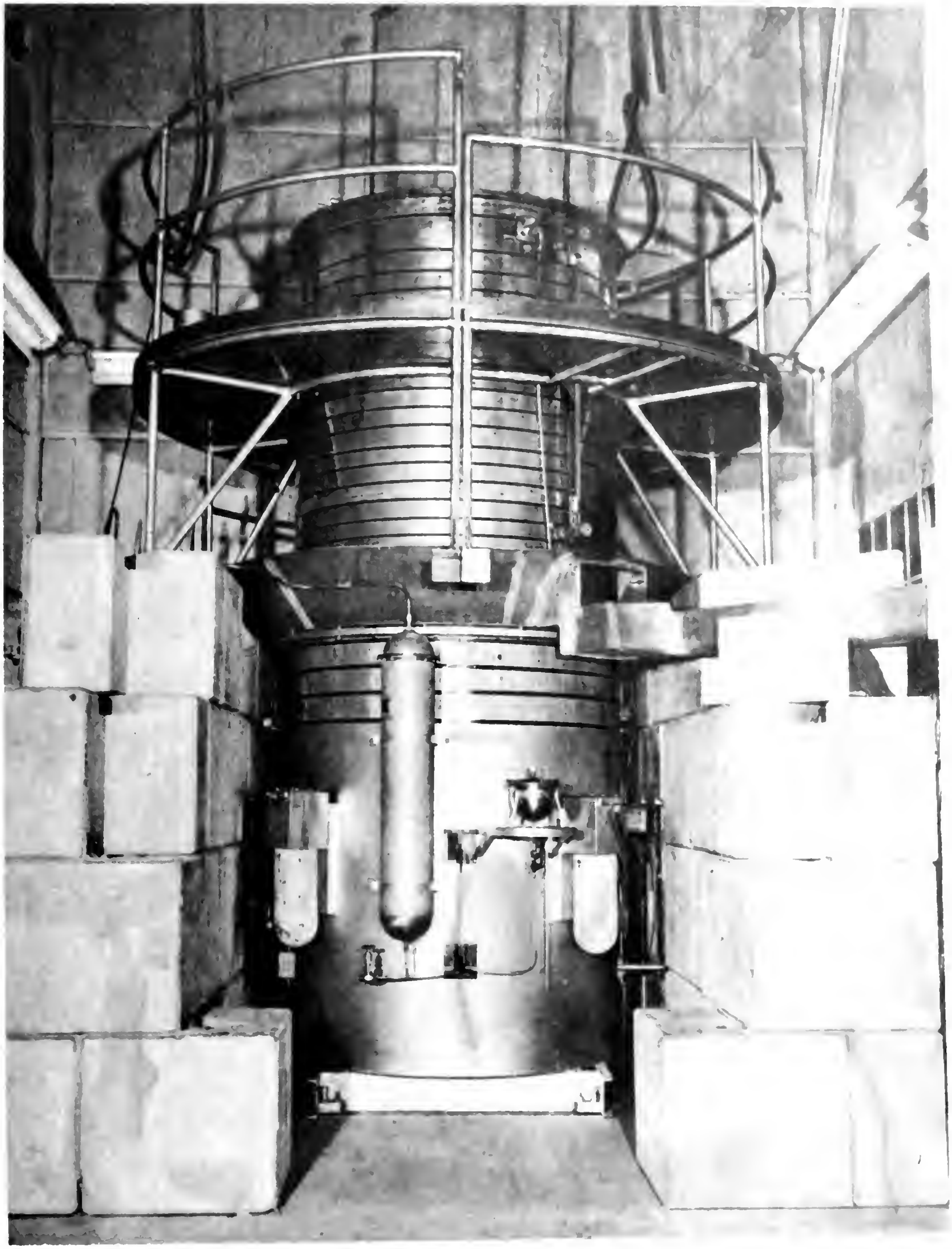


Figure 19.

North American Aviation water boiler

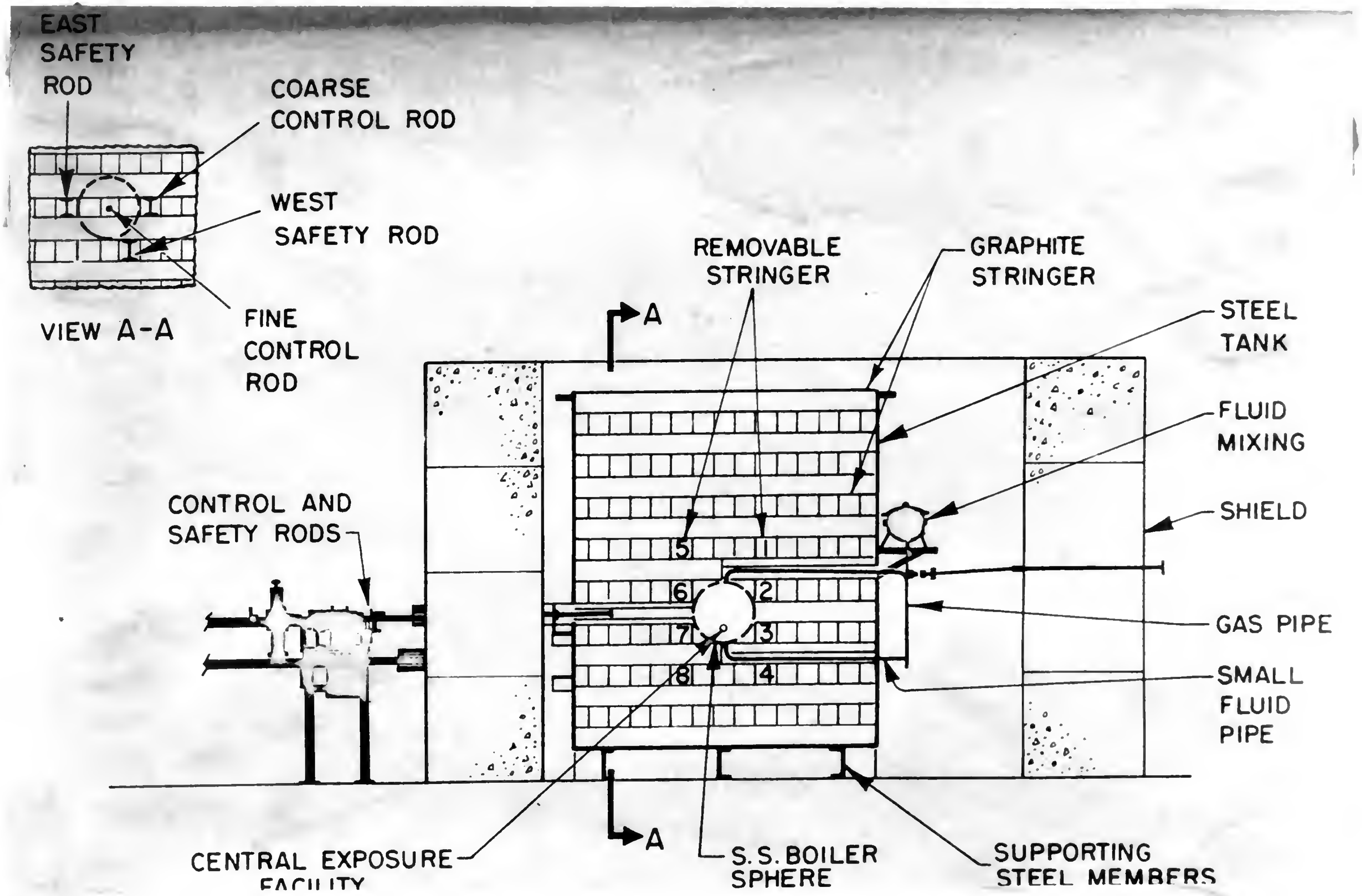


Figure 20.

Chart of North American Aviation water boiler

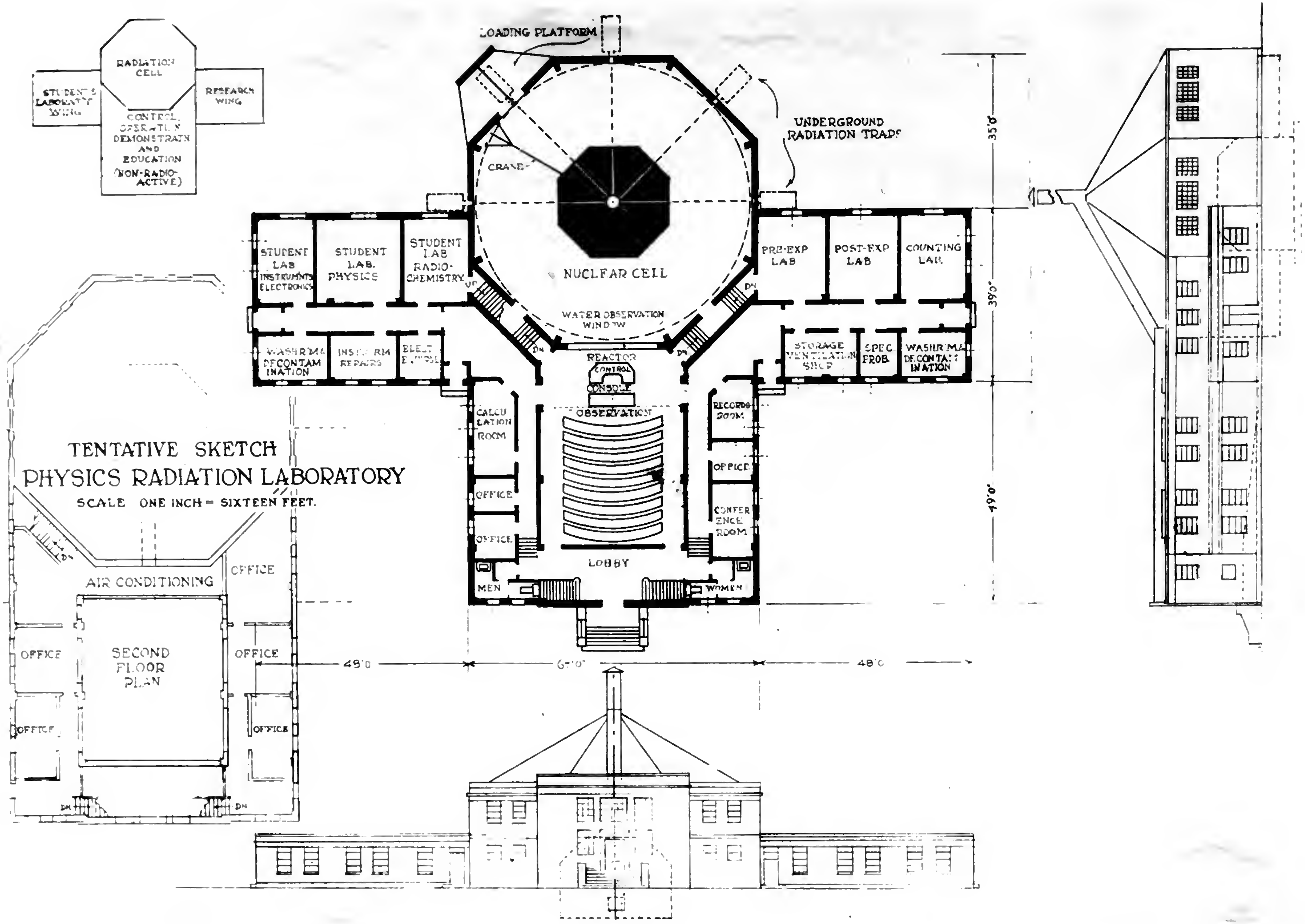


Figure 21.

Suggested floor plan for North Carolina reactor

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Thesis Gibson
G39 Water boiler reactor principles
and evaluation.